DEPARTMENT OF COMMERCE ★ BUREAU OF STANDARDS

NBS TECHNICAL NOTE 879

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Fire Buildup in a Room and the Role of Interior Finish Materials

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Technical note no. 879

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FIRE BUILDUP IN A ROOM AND THE ROLE OF INTERIOR FINISH MATERIALS

J. B. Fang

A variety of wall and ceiling panels in a full-scale room corner have been exposed to a fire from a standardized wood crib, simulating the environment produced by the burning of a single item of furniture, to evaluate their contribution to room fire growth. A total of twenty room corner tests were performed using selected combinations of eight wood-base and gypsum board-base interior finish materials on the walls and ceiling. Gas temperatures and velocities, surface temperatures, heat fluxes, smoke densities, and concentrations of oxygen, carbon dioxide and carbon monoxide were measured. Ignition times of newsprint, cotton fabric and plywood in the lower part of the room were also recorded. The results of these full-scale tests were compared with laboratory tests of the ease of ignition, surface flame spread, heat release rate and smoke generation on the same materials. The maximum upper room gas temperature has been found to agree with the ignition of such indicators as newsprint and plywood, and to represent a measure of fire hazard in terms of potential involvement of all combustible contents or room flashover. A temperature range of 450 to 650°C appears to be the boundary between limited and full involvement.

Key words: Buildings; fire growth; flame spread; heat release; interior linings; material ignitability; performance criteria; room fires; smoke; wood crib.

1. INTRODUCTION

Recent fire loss statistics [1][1] indicate that fires caused by smoking, child-related activities and defects in electric wiring and appliances were responsible for approximately one-third of all building fires and a higher percentage of fire fatalities. These fires generally start small and, in a typical case, may be localized in a wastebasket, upholstered chair or bed. Under certain circumstances, such a small, low intensity, or "incidental" fire may grow into a fully developed room fire. The extent of this fire growth depends on the quantity and type of combustible materials including furnishings, movable contents and structural components located within the room, upon which the fire can feed. Most building codes traditionally regulate the potential fuel contribution of structural components, but not of the movable combustible contents brought in by the building occupants. Accordingly, building code officials are particularly concerned with the increased risk of fire growth in residential occupancies due to combustible interior finish materials, since rapid fire spread on interior surfaces is listed among the major contributors to residential fire fatalities.

Interior finish materials represent a large portion of the area which may be exposed to an accidental fire within buildings. These materials can serve as barriers to fire with little or no contribution of heat and smoke, or may burn as part of the chain of ignitions. It is of practical importance, therefore, to assess the degree of hazard associated in the use of interior finish materials in various locations in buildings and to improve the existing

[1]Numbers in brackets refer to the literature references listed at the end of this paper.

performance standards used as the measurement basis for keeping the hazard within an acceptable level. Many performance standards currently being employ are derived from subjective fire experience; thus, there is little substantiation that the fire ratings or indices obtained from standard laboratory tests can be correlated with the actual level of fire hazard. The objective of this program is to assess the possible correlation between (a) standardized laboratory test evaluations, and (b) the observed fire growth patterns resulting from exposure of wall lining materials to a typical low intensity fire source in a residential room arrangement. While the conclusions reached in this initial study are based on the actual and limited experimental conditions employed, it is hoped that the techniques developed may ultimately serve to assess the extent to which real fire hazards may be predicted by laboratory tests.

A fire originating near the corner of a room formed by the intersection of two adjacent walls, the floor and the ceiling subjects the wall linings to increased radiative and convective heat flux levels due to multiple reflections and confinement of hot combustion gases. Thus, such a corner may constitute a critical configuration for evaluation of the fire performance of interi linings. Furthermore, a corner/room test requires only a limited quantity of test materials (e.g., two wall panels and one ceiling panel) and may be instrumented to provide data on fire growth from initiation of the test up to involvement of typical combustibles in fires or room flashover. In order to compare the flame spread characteristics of various lining materials, corner fire tests have been used to serve as an evaluation tool [2,3] and to demonstrate residential fire hazards [4].

Previous experimental studies have provided information on the fire environment produced by various combustible contents of wastebaskets and individual pieces of upholstered furniture [5,6], and on the development of standardized wood cribs to simulate reproducibly similar levels of low intensi fires in rooms [6,7]. A recent study on reduced scale modeling [8] represents an encouraging approach to the determination of the fire hazards of compound finish materials on walls and ceiling. In order to obtain a better understanding of the physical behavior and prediction of the fire intensity of such small fires, a mathematical description of a freely burning fire [9] has also been developed. This may be used to include the physical, thermal and fire properties of interior lining materials into a prospective thermal analysis of room fire growth.

The growth of a fire in a compartment with combustible linings and sufficient ventilation can generally be described in terms of: ignition; spread of fire across the walls and ceiling; rise of the compartment temperature; and "flashover" or full room involvement. The rate at which a fire builds up depends on the balance between the rate of heat release by the burning materials and the rate of heat loss by absorption in the walls and ceiling, and by venting of the hot gases. A fire hazard rating based simply on flame spread classification does not provide any direct information regarding the rate and amount of heat release by the material as displayed in the room or the resultant heat balance. Whereas a finish material or assembly with high thermal diffusivity may not necessarily contribute appreciably to a serious fire hazard, a material of the same flame spread classification having relatively low diffusivity value might be a potential fire hazard because of the resulting higher temperatures in the enclosing room or building. In a room fire, the rise in temperature of the enclosure walls and the hot gas beneath the ceiling creates increased radiant and convective heat flux levels which serve to produce new ignitions and enhance the rates of flame spread and heat release. Evaluating the fire performance of a material in a room configuration is realistic since the material behavior in a fire depends considerably on the environment to which it is exposed. However, due to the expense of large-scale testing and the large number of possible arrangements and sizes of the room, it has not been considered practicable to employ full-scale corne room testing as a general evaluation tool in place of laboratory testing.

Therefore, this study was limited to: (a) an initial evaluation of fire growth in a particular room arrangement and a few selected materials, and (b) comparisons with several laboratory test methods, including the ASTM E84 Tunnel Test referred to in most building codes.

2. EXPERIMENTAL DETAILS

2.1. Test Compartment

Figure 1 is a plan view of the burn room showing the locations of wall panels and a standardized wood crib in a room corner, and the arrangement of instrumentation. All full-scale tests were conducted in a burn room having a 2.9 x 3.2 m (9.5 x 10.5 ft) floor with a ceiling height of 2.4 m (7.9 ft). An open doorway measuring 0.9 m (35 in) wide by 2 m (80 in) high near the corner in the south wall (one of the smaller compartment walls) represented a typical situation involving a single source of ventilation for the room.

The basic construction of the test compartment was reinforced concrete with the wall and ceiling lined with 16 mm (5/8 in) thick, type "X" gypsum wallboards mounted to 51 x 102 mm (2 x 4 in) steel studs and finished with a vermiculate gypsum plaster. Sand was placed over the brick subfloor. The entire test compartment was situated within a large building to minimize exterior weather effects.

2.2. Instrumentation

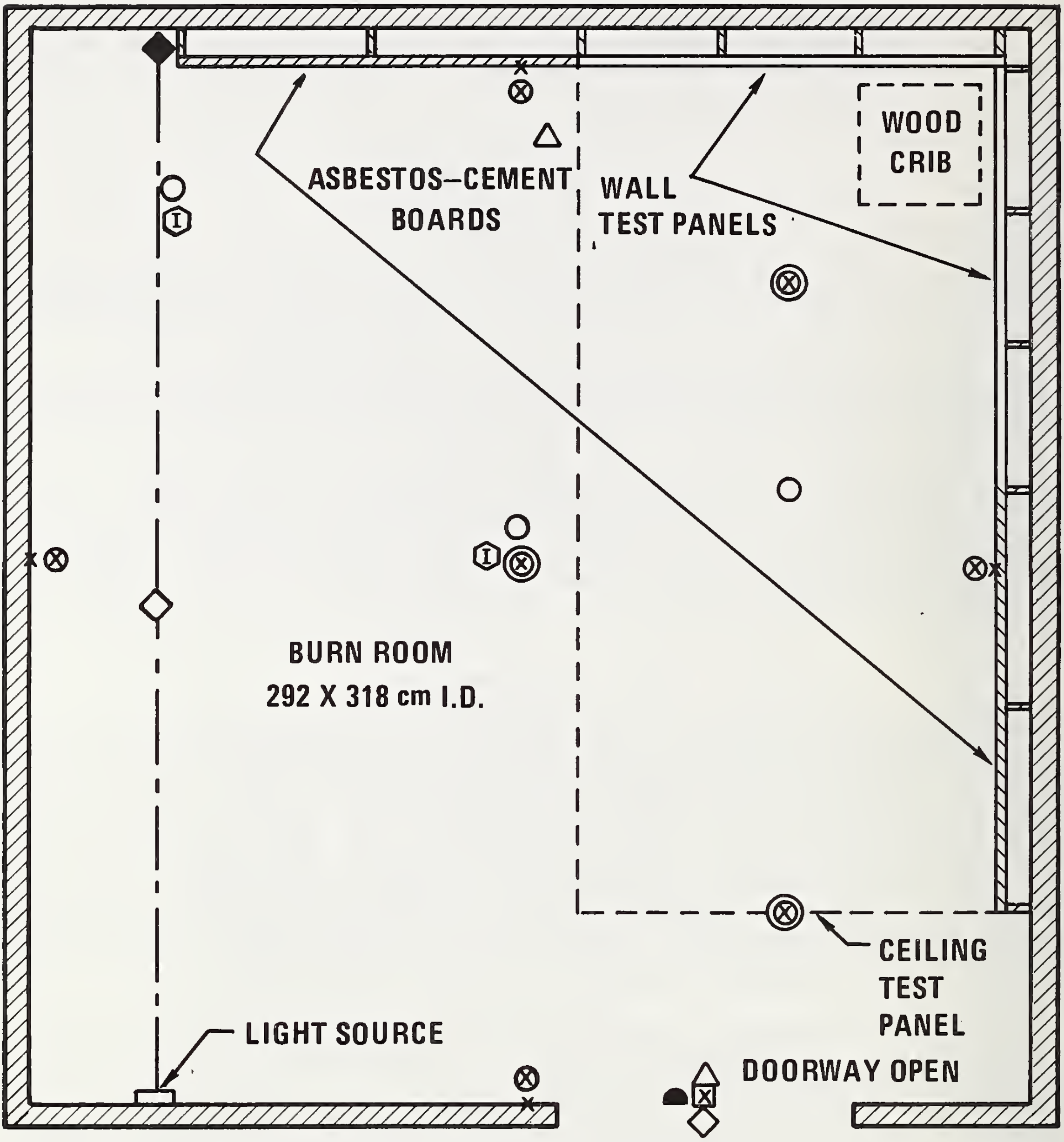
Temperature measurements were made with 36 thermocouples placed at the selected locations inside the test compartment, as shown in figure 1, three positioned along the flame axis above the wood crib, and 49 thermocouples attached on both exposed and unexposed surfaces of the test panels. All bare beaded thermocouples were of No. 24 B. and S. gage (0.51 mm wire diameter) chromel and alumel wires. A total of eight Gardon type radiometers mounted on the walls, ceiling and floor were used for measuring the heat flux levels including the thermal radiation from hot ceiling and upper walls, and the layer of hot gases and flames. The vertical distribution of the horizontal component of gas velocity at the doorway was measured by four pitot tubes in conjunction with variable reluctance pressure transducers.

In order to determine its weight loss rate during burning, the standardized wood crib was located on a weighing platform supported on a 227 kg (500 lbs) capacity strain gage load cell.

The levels of smoke density at various locations were monitored by measuring the attenuation of a collimated visible light beam impinging on a photocell. Both the light sources and the photomultiplier tubes were protected from smoke deposition by air purging. Smoke measurements were made at three locations shown in figure 1 -- one horizontal measurement at 1.5 m (5 ft) height within the compartment, and two vertical measurements, one near the left-center of the room, and the other at the doorway. These arrangements permitted the measurement of relative values for the smoke accumulated within the compartment or convected through the door opening.

Continuous measurements of carbon monoxide, carbon dioxide and oxygen concentrations at a height of 76 mm (3 in) below the ceiling within the room and at the upper edge of the doorway were made by extracting gas samples and determining concentrations with infrared gas analyzers.

Three indicator specimens of ordinary newsprint, 0.19 mm thick white cotton fabric and 6.4 mm thick fir plywood commonly found in dwellings were placed within the test compartment to provide a direct indication of the



◊ VERTICAL SMOKE METER

○ RADIOMETER

◓ PITOT TUBES

◆ HORIZONTAL SMOKE METER

△ GAS SAMPLING LOCATION

Ⓘ INDICATOR SPECIMEN S

X THERMOCOUPLE PLACED AT 122 cm BELOW THE CEILING

⊗ 2 THERMOCOUPLES, RESPECTIVELY AT 2.5 AND 122 CM BELOW THE CEILING

⊗ 5 THERMOCOUPLES, AT 2.5, 25, 81, 122 AND 183 CM BELOW THE CEILING

☒ 9 THERMOCOUPLES AT THE DOORWAY

Figure 1. Plan View of the Burn Room Showing Locations of Test Panels and Wood Crib, and Arrangement of Instrumentation.

involvement of typical combustibles in fires. These indicators, each consisting of two 102 x 152 mm sheets and formed in a "L" shape with one sheet held parallel to the floor, were placed at two locations as shown in figure 1: near one room corner and at the center of the floor, respectively at heights of 500 and 100 mm above the floor.

In each test, a total of 110 channels of the output signals from thermocouples, heat flux meters, load cell, pitot tubes, smoke meters and gas analyzers were directly recorded every 10 seconds on a magnetic tape by a high speed digital data acquisition system. The data were processed, tabulated and plotted by the digital computer.

2.3. Test Specimens and Standardized Wood Cribs

Eight interior finish materials typical of those used in residential dwellings and 127 mm (1/2 inch) thick bare asbestos-cement board were selected for this test program. They represent a wide range of flame spread and smoke levels. A summary of surface treatments, nominal thickness and bulk density of these interior finish materials are presented in table 1 along with their identification symbols.

Two types of standardized wood cribs, developed to simulate the fire environments due to incidental fires, were employed to serve as ignition sources. A large sized crib, measuring 560 x 560 x 550 mm (22 x 22 x 21 3/4 in) high and weighing approximately 33 kg (72 lbs) consisted of 34 pieces of nominal 51 x 102 x 560 mm (2 x 4 x 22 in) long hemlock sticks nailed into a lattice to represent a moderate intensity furniture fire. A smaller 360 x 360 x 300 mm (14 x 14 x 12 in) high crib weighing about 6.3 kg (14 lbs) and constructed by piling 28 pieces of nominal 51 x 51 x 360 mm (2 x 2 x 14 in) long sticks was used to simulate an incidental fire of shorter flame length and duration. The large crib had eight layers, each containing four sticks with a 63.5 mm (2.5 in) stick spacing, plus a bottom layer containing two sticks. The small sized crib consisted of six four-stick and two two-stick layers and the spacing between sticks, except for the bottom two layers, was 51 mm (2 in). The moisture content of the wood cribs was approximately 9 percent, as measured with an electrical resistance moisture meter.

3. TEST PROCEDURE

Three 1.2 x 2.4 m (4 x 8 ft) full sized test panels were used to cover a room corner opposite of the doorway. Two wall panels were mounted at a spacing of 89 mm (3.5 in) from the two adjacent walls on steel studs extending from floor to ceiling. One ceiling panel, with its 2.4 m length running towards the doorway, was nailed directly to wood furring strips whose thickness provided an air space of approximately 19 mm (3/4 in) between the panel and the ceiling, (see fig. 1). A standardized wood crib was situated on the weighing platform placed close to the corner at 254 mm (10 in) above the floor and 51 mm (2 in) away from the test wall panels. Photograph 1 shows the position of the wood crib in a room corner prior to ignition, and a portion of instrumentation arrangement as viewed from the open doorway.

The test was started by application of an open flame to ignite 80 ml of ethanol in a 203 x 203 x 25 mm (8 x 8 x 1 in) deep steel pan placed beneath the crib. Visual observations and a photographic record of the fire buildup process were made during the course of several of the tests. Data were collected until spontaneous ignition of specimen indicators occurred, which usually required a minimum of 8 minutes, although the tests were extended beyond this time for materials which did not cause full flame involvement.

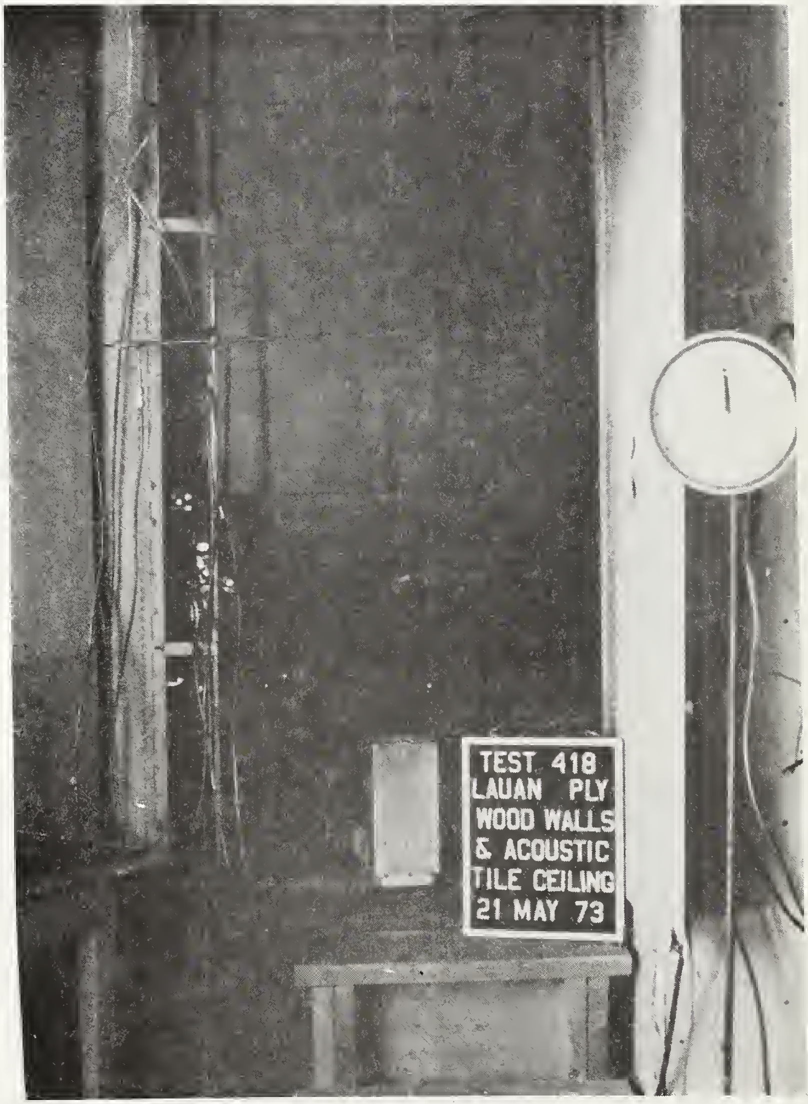


Photo 1. Test Arrangement Before Ignition Viewed Through the Open Door.

Table 1. Descriptions of Materials Used and the Results of Laboratory Tests on Ease of Ignition, Surface Flame Spread, Heat Release and Smoke Generation

Material					Ease of Ignition	Flame Spread Index		Heat Release		Smoke		
Symbol	Name	Thickness mm	Thickness in	Bulk Density (g/cm^3)	Ignition Time (min)	ASTM E84 Tunnel	ASTM E162 Radiant Panel	Rate (W/cm^2)	Total (J/cm^2)	NBS Chamber (Dm) Flaming	NBS Chamber (Dm) Non-Flaming	ASTM E84 Tunnel Classification
G	Gypsum wallboard finished with 2 coats of white latex paint	12.7	1/2	0.71	∞	24	8	7.4	540	33	51	7
V	Vinyl covered gypsum wallboard, cloth textured surface	12.7	1/2	0.76	∞	33	23	5.9	580	54	85	55
P	Particle board, unfinished	15.9	5/8	0.71	2.55	153	118	20.6	13,400	398	570	160
F	Douglas fir ply-wood prefinished 3-ply	6.4	1/4	0.68	1.75	103	135	15.8	4,580	146	445	86
L	Lauan plywood sanded unfin-ished 3-ply	4.4	11/64	0.50	1.58	167	141	16.5	2,720	50	310	67
M	Melamine fin-ished tempered hardboard	3.2	1/8	1.17	2.51	226	117	52.4	6,100	89	465	230
A	Acoustic tile (fiber board base) painted holes	12.7	1/2	0.32	1.23	101	60	12.2	5,840	113	261	61
C	Coated acoustic tile (mineral-base coating on fiber board base)	12.7	1/2	0.32	∞	70	6	6.1	3,020	73	97	20

4. TEST RESULTS

The photographic records of the development of an experimental fire with Lauan plywood walls and acoustic tile ceiling in the full sized test compartment are shown in photos 2 to 4. Photos 4 to 6 illustrate active burning stage of the tests involving different types of wall lining materials exposed to a common ignition condition. These observations reveal that the rate and extent of fire development depend considerably on the nature of lining materials involved.

In order to determine the experimental variables to which results in the full-scale room corner tests were sensitive and the variability of present test procedure, three test conditions including the size of wood crib, type of wall lining material and choice of ceiling finish material were selected to be explored for their possible effects on the maximum upper room gas temperature and the peak one minute average smoke density within the fire compartment. For this test series, two materials used to cover the walls and ceiling of a room corner were painted gypsum wallboard and particle board. They were each exposed to the two ignition sources: the large and small standardized wood cribs. Repeat tests were performed on eight randomly selected combinations of experimental conditions as tabulated in table 2. This table also gives the maximum values of the upper room gas temperature and the smoke density of the duplicate test runs for each of the eight combinations.

By applying a statistical technique on factorial designs [10], the estimated standard deviations of replication error were found be 27°C for the upper room gas temperature and 0.08 optical density/m (OD/m) for smoke density measurements. The optical density/m is a measure of the density of light-obscuring smoke suspended in a volume, and is defined as the optical density, or the common logarithm of the ratio of the intensity of the incident light to that of the transmitted light, measured over 1 m of light path length. The changes in crib size and type of materials on walls and ceiling all produced significant variation in the upper room gas temperature at the 95% confidence level. It was found that the conditions exerting important influences on smoke density measurement included the size of wood crib and type of wall lining material. The change made in the type of ceiling finish material had an insignificant effect on the results at this level. A detailed calculation based on summary data presented in table 2 is given in Appendix A.

The experimental results of full-scale corner fire tests on time to ignition, surface flame spread, time to flame penetration, maximum smoke density, maximum upper room gas temperature, and time to flames emerging from the doorway for selected combinations of eight finish materials used as wall and ceiling linings are summarized in table 3. The data show that the elapsed time for ignition of wall panels ranged from about 2 minutes for acoustic tile (test 16) to approximately 3.5 minutes for vinyl covered gypsum board (tests 8, 13). The rate of weight loss of the small wood crib at ignition of the wall materials varied from 0.38 to 0.51 kg/min with an average of 0.44 kg/min. The maximum weight loss rate was found to range from 0.43 kg/min for painted gypsum board to 0.79 kg/min for melamine finished hardboard walls, depending on the feedback energy of the burning walls and ceiling involved. The weight loss rate of the large crib was estimated to be of the order of 1.1 kg/min.

Excluding the tests the painted gypsum wallboard and vinyl covered gypsum board which burned only to a vertical distance of about 0.5 m, the time taken after ignition for flames to travel up the 1.8 m high wall to reach the ceiling varied from 19 seconds (0.32 min) for Lauan plywood to 52 seconds (0.87 min) for acoustic tile. The data also suggest that for the same type of material (except particle board), the rate of horizontal flame spread across the ceiling was generally higher than that vertically along the wall surface, and was strongly dependent upon the type of wall lining material. The spread of flames across the ceiling was enhanced by radiant and convective heating due to the burning of the upper walls. Except for particle board, painted gypsum

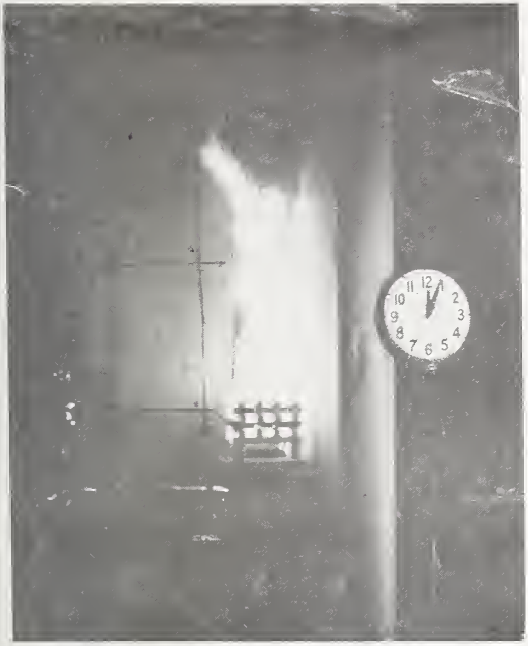
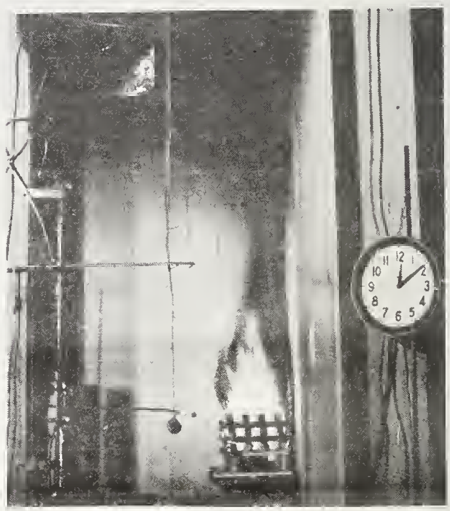


Photo 2. Spread of Fire Along Wall Panels, 4 Min After Ignition.

Photo 3. Involvement of Ceiling Lining, 6 Min After Ignition.

Photo 4. Active Burning Stage, 8 min after Ignition, for Test Fire Involving Lauan Plywood Walls and Acoustic Tile Ceiling.

Photo 5. Fire Development, 9 min after Ignition, for Test Fire Involving Painted Gypsum Board Walls and Acoustic Tile Ceiling.



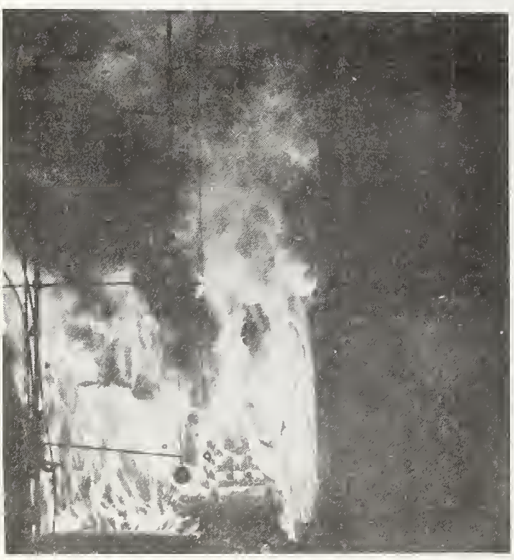


Photo 6. Fire Development, 8 min after Ignition, for Test Fire Involving Melamine/Hardboard Walls and Acoustic Tile Ceiling.

Table 2. Eight Combinations of Test Conditions and Duplicate Test Results on the Maximum Upper Room Gas Temperature and the Maximum One Minute Average Room Smoke Density

Variables		Combination 1	2	3	4	5	6	7	8	S
Test Condition	Crib Size	X	X	X	X	x	x	x	x	
	Wall Material	Y	Y	y	y	Y	Y	y	y	
	Ceiling Material	Z	z	Z	z	Z	z	Z	z	
Duplicate Test Results	Maximum Upper Room Gas Temperature (°C)	129	136	532	719	376	442	550	698	
		146	134	549	753	345	456	641	674	27.1
	Maximum Smoke Density (OD/m)	0.33	0.21	0.82	0.94	0.25	1.42	1.32	0.55	
		0.37	0.10	0.91	0.78	0.12	1.35	1.28	0.75	0.083

Letter designations: X and x represent small and large wood crib, respectively; Y and y represent painted gypsum wallboard and particle board walls, respectively; Z and z represent painted gypsum wallboard and particle board ceiling, respectively.

S is standard deviation of the replication error for a single test value.

Table 3. Results of Full-Scale Room Corner Tests with Selected Combinations of Finish Materials as Wall and Ceiling Linings

Test No.	Materials: Walls	Materials: Ceiling	Time to Ignition (min): Wall	Time to Ignition (min): Ceiling	Surface Flame Spread On Wall: Max. Distance (m)	Surface Flame Spread On Wall: Duration Time (min)	Surface Flame Spread On Ceiling: Max. Distance (m)	Surface Flame Spread On Ceiling: Duration Time (min)	Time to "Flame-Through" (min): Wall	Time to "Flame-Through" (min): Ceiling	One Minute Average Max. Smoke Density (OD/m): Room	One Minute Average Max. Smoke Density (OD/m): Doorway	Max. Upper Room Gas Temperature (°C)	Time to "Flame Emerging from Doorway" (min)
1	Particle board	Particle board	3.2	3.8	1.83	0.43	2.21	0.80	∞	∞	0.94	0.91	719	5.4
2	Fir Plywood	Gypsum board	2.2	2.8	1.83	0.53	2.21	0.82	6.0	∞	0.75	0.44	571	∞
3	Lauan Plyw'd	Gypsum board	2.5	2.8	1.83	0.32	2.21	0.73	5.3	∞	0.62	0.38	439	∞
4	Gypsum Board	Particle Bd.	3.2	∞	0.53	0.57	0	∞	∞	∞	0.21	0.10	136	∞
5	Gypsum Board	Gypsum Board	2.8	∞	0.53	0.35	0	∞	∞	∞	0.29	0.08	129	∞
6	Particle Bd.	Gypsum Board	2.6	3.0	1.83	0.35	2.21	0.90	∞	∞	0.91	0.72	549	5.7
7	Melamine/ Hardboard	Gypsum Board	3.2	3.7	1.83	0.48	2.21	0.73	5.3	∞	0.97	0.85	662	5.3
8	Vinyl/Gyp-sum Board	Gypsum Board	3.4	∞	0.61	0.67	0	∞	∞	∞	0.30	0.17	147	∞
9	Gypsum Board	Acoustic Tile	3.4	∞	0.53	0.47	0	∞	∞	∞	0.16	0.08	136	∞
10	Fir Plywood	Acoustic Tile	2.8	3.2	1.83	0.32	2.21	0.63	6.1	6.1	0.88	0.84	683	4.9
11	Lauan Plyw'd	Acoustic Tile	3.3	3.7	1.83	0.33	2.21	0.68	5.0	9.7	0.44	0.27	508	6.9
12	Melamine/ Hardboard	Acoustic Tile	3.5	4.1	1.83	0.63	2.21	0.60	5.2	8.4	0.94	0.66	701	5.6
13	Vinyl/Gyp-sum Board	Acoustic Tile	3.4	∞	0.61	0.52	0	∞	∞	∞	0.21	0.15	153	∞
14	Particle Board	Acoustic Tile	3.1	3.6	1.83	0.52	2.21	0.72	∞	8.9	0.78	0.50	705	5.6
15	Melamine/ Hardboard	Melamine/ Hardboard	3.2	3.7	1.83	0.65	2.21	0.60	5.0	5.2	1.06	0.95	803	4.4
16	Acoustic Tile	Acoustic Tile	2.1	2.9	1.83	0.77	2.21	0.67	9.8	8.1	0.29	0.09	537	6.1
17	Acoustic Tile	Gypsum Board	2.3	3.1	1.83	0.87	0.99	0.30	8.6	∞	0.53	0.17	390	∞
18	Coated Acoustic Tile	Coated Acoustic Tile	2.3	2.7	1.83	0.34	0.69	0.17	8.1	∞	0.12	0.09	448	∞
19	Coated Acoustic Tile	Gypsum Board	2.1	2.8	1.83	0.63	0.15	0.20	10.7	∞	0.14	0.11	299	∞
20	Asbestos Cement Board	Asbestos Cement Board	∞	∞	0	∞	0	∞	∞	∞	0.11	0.07	107	∞

wallboard and vinyl covered gypsum board, the time to "flame-through", i.e. to burn completely through the panel, varied from 5 to 11 minutes and was dependent upon the chemical composition and thickness of the material involved.

The maximum concentrations of smoke based on a one minute average generated within the ventilated compartment by painted gypsum board (tests 4,5,9), vinyl covered gypsum board (tests 8,13) and asbestos cement (test 20) walls under crib flame exposure condition were of the order of 0.2, 0.3 and 0.1 OD/m respectively. The data also show that the walls covered with melamine finished hardboard (tests 7,12,15) and those with particle board (tests 1,6) produced the highest levels of smoke density and those with coated acoustic tile (tests 18,19) the least. For all tests, the times taken to reach peak smoke levels were found to range from 1.5 to 7 minutes after the onset of ignition on the test panel.

The temperature of the gases within the upper half of the test compartment was calculated by averaging of the temperatures of room gas at 10 locations; 5 at mid-height and the other 5 at 25 mm below the ceiling. This upper room gas temperature is believed to directly relate to the possibility of full involvement of the combustible room contents. As shown in table 3, the peak temperatures of the upper room gas varied from approximately 130°C for painted gypsum board panels (test 5) to 800°C for melamine finished hardboard walls and ceiling (test 15), depending on the type, thickness and arrangement of the panels.

Flames emerging from a doorway or from a window opening can initiate the spread of fire along a corridor and adjacent rooms or to the upper stories of the building. In these tests, the time elapsed between ignition of the starter fuel beneath the crib and flame emerging from doorway was obtained from visual observations and was found to vary from about 4.5 minutes to infinity (i.e. no emergent flames) depending on the nature of the linings involved.

The times taken for spontaneous ignition of the indicators were observed visually and found to depend upon the nature and location of the specimen involved. In general, the newsprint was the easiest and the plywood the hardest to ignite. Also, the indicator specimens near the room corner ignited earlier than those at the center of the floor. The incident heat flux measured at the center of the floor corresponding to the ignition of newsprint and plywood was found to range from 1.7 to 2.5 W/cm^2 and 2.1 to 3.3 W/cm^2, respectively.

Figure 2 shows a plot of upper room gas temperature at which newsprint or fir plywood indicators placed at the room center was ignited versus the elapsed time between initiation of the test and ignition of the indicator involved. The fire conditions required to cause ignition of these typical combustibles was considered critical as they could ultimately lead to full room fire involvement and spread of fire to other rooms, and thus affect the survival of the occupants and property. As shown in figure 2, the upper room gas temperature at which the indicator was ignited varied from test to test, and ranged from 458 to 638°C for ignition of newsprint and 531 to 681°C for ignition of plywood. Visual observation and experimental data indicate that the induction times for ignition of these indicator specimens were considerably shorter than the elapsed time between involvment of wall linings and onset of ignition on the indicators. Also, the level of heat flux imposing on the indicators from the developing fire was time variant depending upon the fire buildup process or the type of finish materials used. For the purpose of estimating the condition leading to involvement of all combustible contents or room flashover, the average upper room gas temperatures necessary for spontaneous ignition of newsprint and plywood panel placed at the center of the floor were 540 $\pm$ 40°C and 590 $\pm$ 40°C, respectively, based on 95% confidence level. As shown in the figure, the time taken to ignite newsprint and plywood varied from 5 minutes for melamine finished hardboard walls and ceiling to approximately 9 minutes for acoustic tile linings. The experimental data presented in figure 2 are tabulated in table 4.

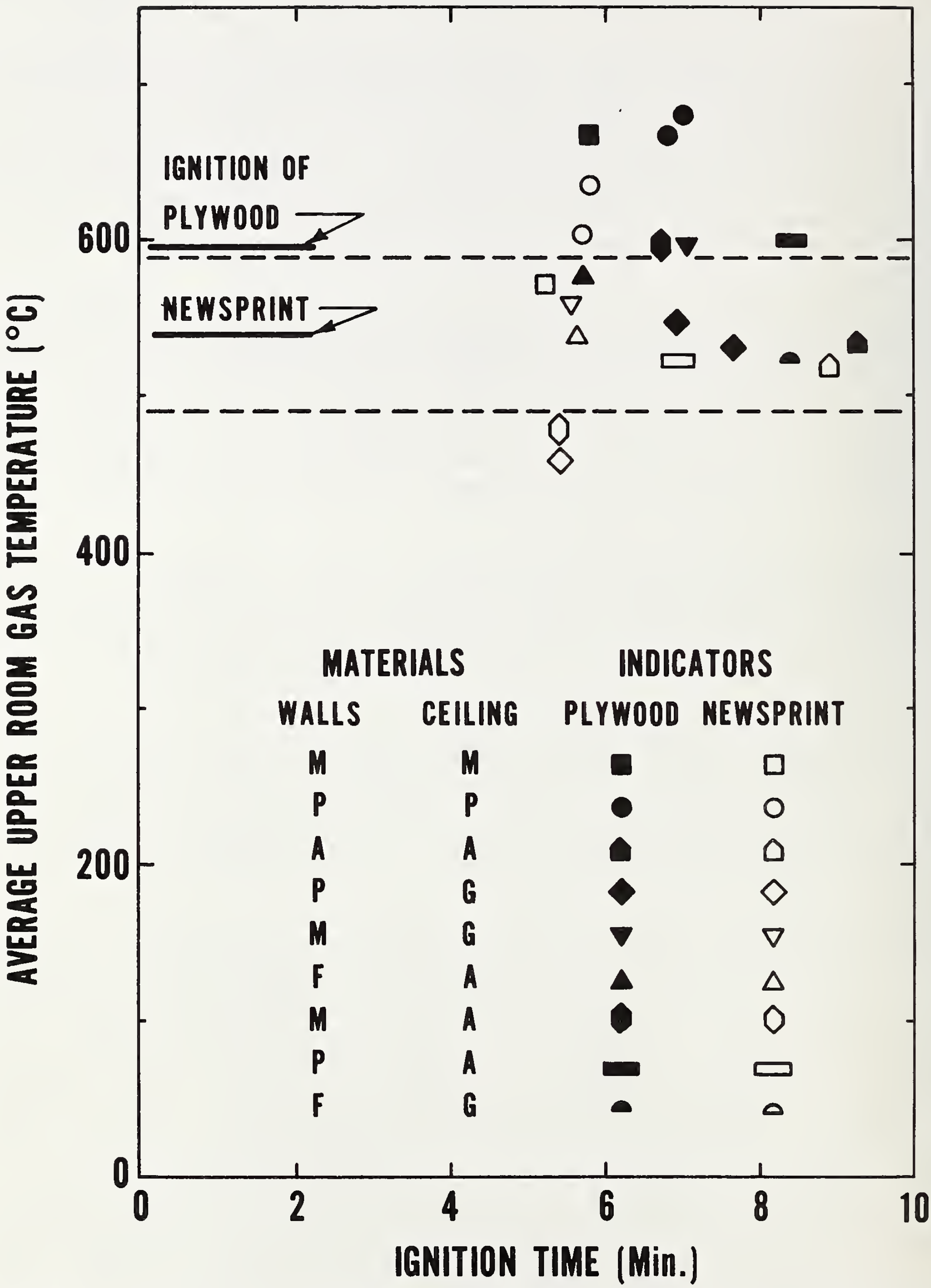


Figure 2. A plot of the average upper room gas temperature at which specimen indicator was ignited versus ignition time. Identification symbols for these lining materials are given in table 1. Dashed lines represent one standard deviation limits for newsprint.

Table 4. Ignition Times of Newsprint and Plywood and the Upper Room Gas Temperatures at which the Indicators were Ignited Spontaneously.

Materials		Newsprint		Plywood	
Walls	Ceiling	Ignition Time (min)	Upper Room Gas Temperature (°C)	Ignition Time (min)	Upper Room Gas Temperature (°C)
Particle Board	Particle Board	5.7	605	7.0	681
Fir Plywood	Painted Gypsum Board	—	—	8.4	521
Particle Board	Painted Gypsum Board	—	—	6.9	545
Melamine / Hardboard	Painted Gypsum Board	5.5	563	7.0	592
Fir Plywood	Acoustic Tile	5.6	535	5.7	572
Melamine / Hardboard	Acoustic Tile	5.4	473	6.7	600
Particle Board	Acoustic Tile	6.9	518	8.4	603
Melamine / Hardboard	Melamine / Hardboard	5.2	570	5.8	670
Acoustic Tile	Acoustic Tile	8.9	519	9.2	533
Particle Board	Painted Gypsum Board	5.4	458	7.6	531
Particle Board	Particle Board	5.8	638	6.8	668

Some typical vertical gas temperature profiles at three locations inside the fire room for a test where spontaneous ignition of the plywood indicator occured at 9 minutes, and one test where no ignition took place is given in figure 3. These profiles illustrate the convective flow pattern inside the test compartment, and also show the presence of vertical stratification and non-uniform distribution of temperature attributed to the induced cooling draft along the floor and heat released by burning the lining materials. It can be seen that the temperature of the gases immediately above the plywood indicator located at the center of the room was usually less than 370°C, which was the measured ignition temperature for plywood [7]. It appears that the lower part of the walls and floor were actually heated by radiation from the upper walls, ceiling and combustion gases, while being cooled by forced convection of the inflowing cool air. Upper room gas and ceiling radiation thus play a major role in heating the lower part of the room in a fire.

Figure 4 shows plots of the composite horizontal velocity and temperature profiles of the combustion gas at the open doorway for a test with fir plywood walls and acoustic tile ceiling. These are taken at the time when the flame first emerges from the doorway (295 sec) and when the upper room gas temperature is maximum (420 sec). These experimentally determined gas temperatures shown in the figure were not corrected for radiation effect. The temperature profiles exhibit the vertical stratification as a result of the smoke and combustion products venting from the fire room along the ceiling and cool air coming in through the lower portion of the doorway.

The variation with time of the average upper room gas temperature for fires involving several different types of lining materials is shown in figure 5. The curves have been smoothed to simplify the presentation of data; they retain the major features and relative effects. The upper room gas temperature data of a blank test in which 6.4 mm (1/4 in) thick asbestos-cement boards were used as wall and ceiling finish materials are also plotted in the same figure for comparison. It can be seen that the maximum gas temperature increas from 130°C for painted gypsum board walls and ceiling, to approximately 420°C for Lauan plywood walls and gypsum board ceiling, 660°C for melamine finished hardboard walls and gypsum board ceiling, and 510°C for Lauan plywood walls and acoustic tile ceiling. During the test with melamine/hardboard walls and gypsum board ceiling, all indicator specimens including newsprint, cotton and plywood were found respectively to ignite at times ranging from 6 to 7 minutes. As indicated in the figure, the gas temperature within this time interval rose rapidly and exceeded 550°C which is an upper room gas temperature at which newsprint ignites readily. The temperature of the upper room gas resulting from the burning of the standardized wood crib in the room lined with asbestos-cement board increased at a relatively constant rate of approximately 1°C per minute after 3 minutes due to a decrease in heat dissipated into the enclosure walls as shown in the data of the blank test.

Figure 6 shows comparison plots of the time sequence of convective and radiative heat-transfer-rates from the test room through the doorway to the outside, for fires with different combinations of interior finish materials. The energy transfer calculations were made with the assumptions that both the velocity and temperature distributions can be approximated by a finite number of linear segments, the doorway opening can be considered as a blackbody emitter with a uniform temperature, and the flue gas behaves as an ideal gas for temperature correction on velocity measurements by pitot tubes, and has the same thermal properties as air. From the figure, it appears that the radiative contribution comprised approximately 10 percent of the total available energy to the outside due to the relatively low gas temperature and the small size of the doorway opening. The bulk of the convective energy was discharged to the outside by way of a hot turbulent jet or stream issuing from the upper portion of the doorway and its magnitude strongly depended upon the material type and arrangement of the interior linings involved.

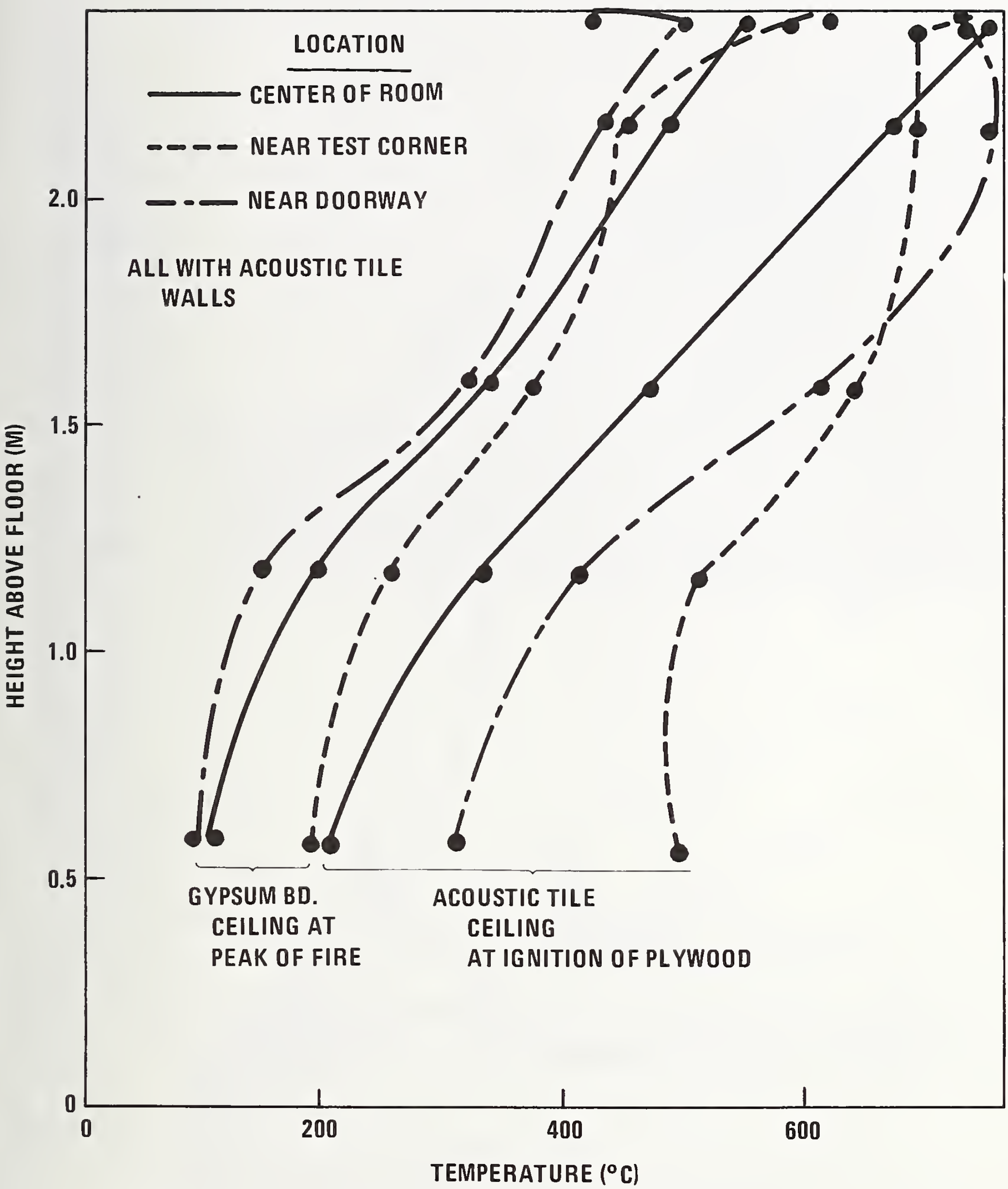


Figure 3. Vertical gas temperature profiles at various locations within the fire room.

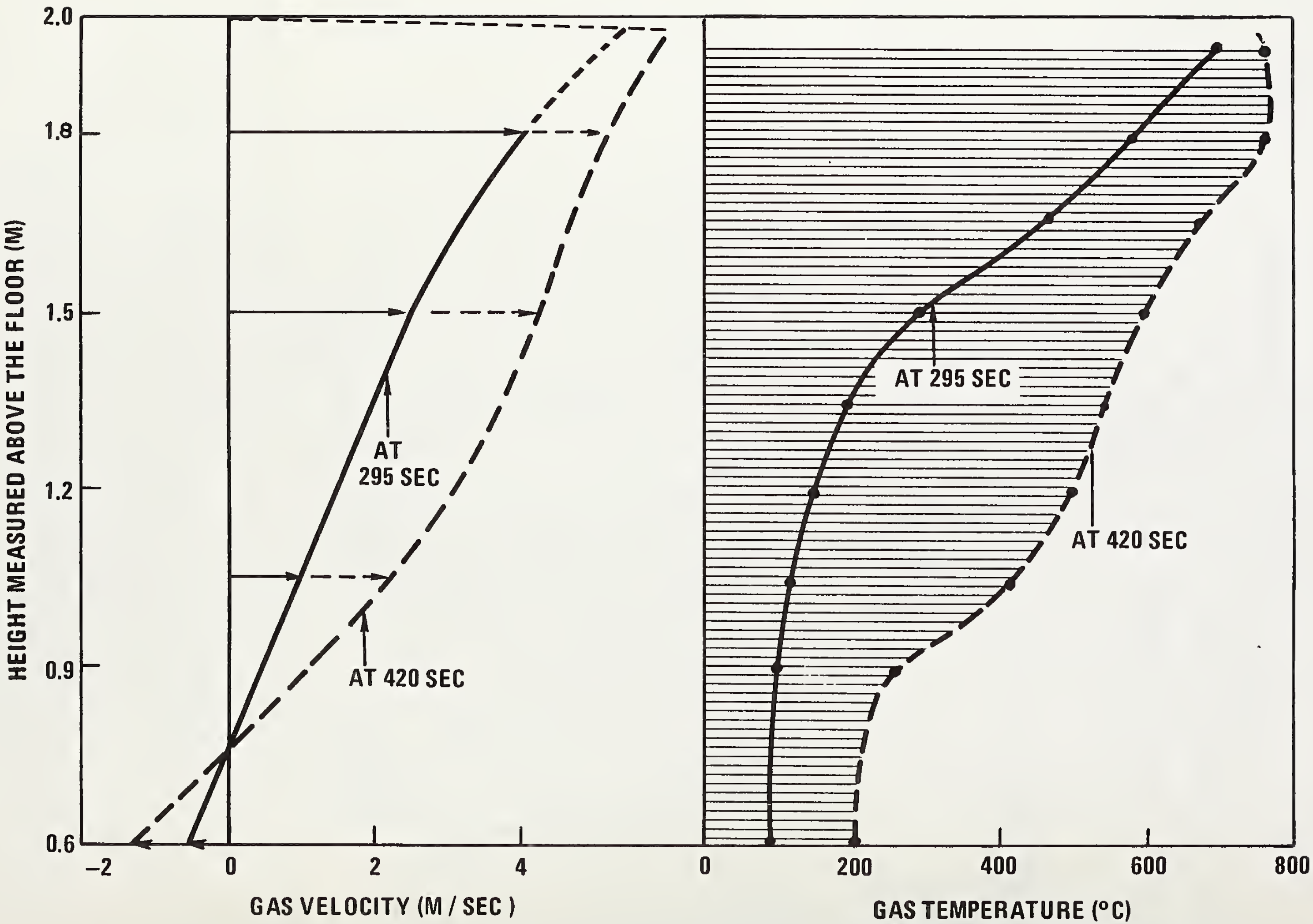


Figure 4. Vertical distributions of velocity and temperature of effluent gas at the doorway at times of flames Out-Of-The-Doorway and at the peak of the fire with fir plywood walls and acoustic tile ceiling.

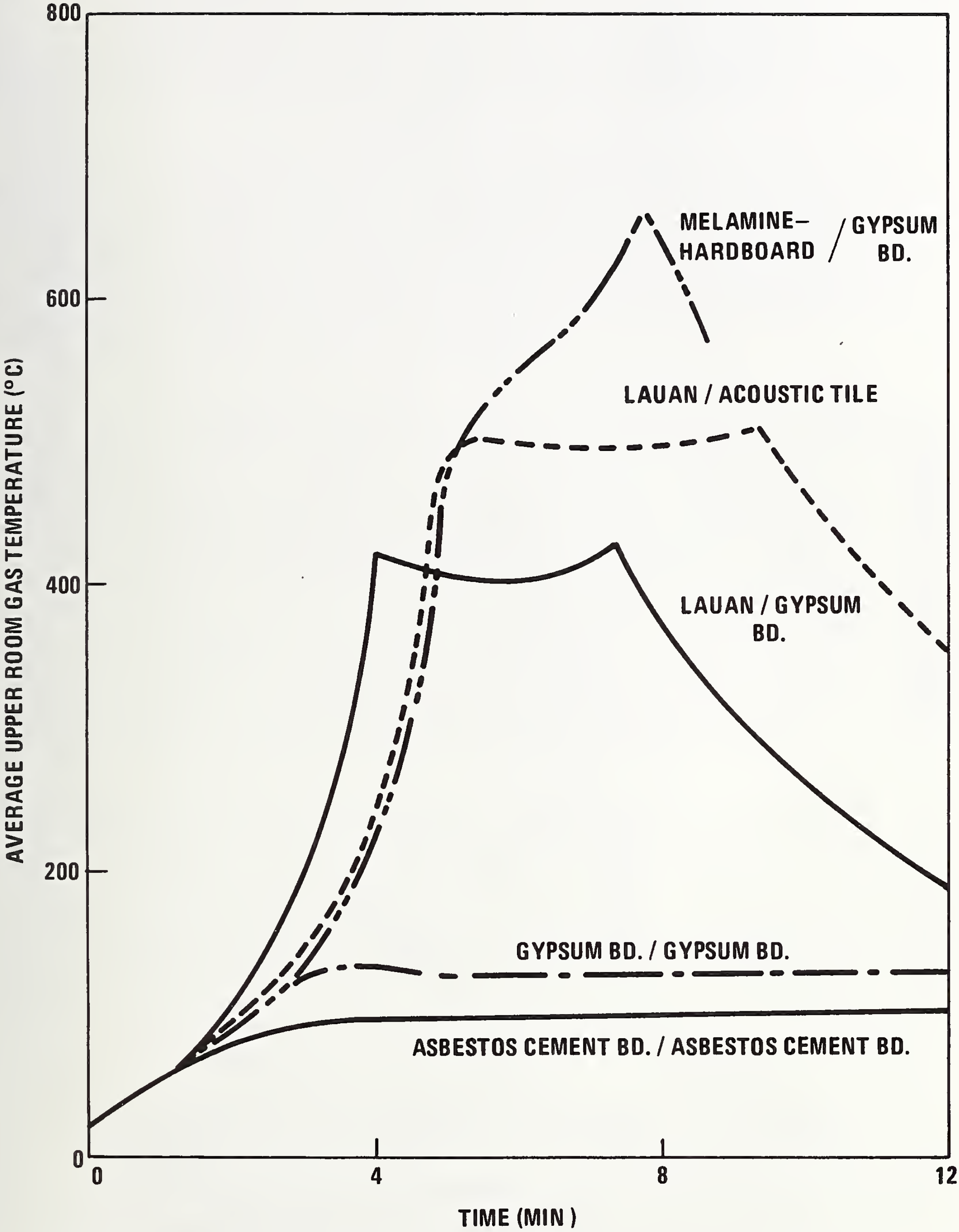


Figure 5. Effect of material combination of wall and ceiling linings on spatial average upper room gas temperature. Legends on curves indicate wall/ceiling materials.

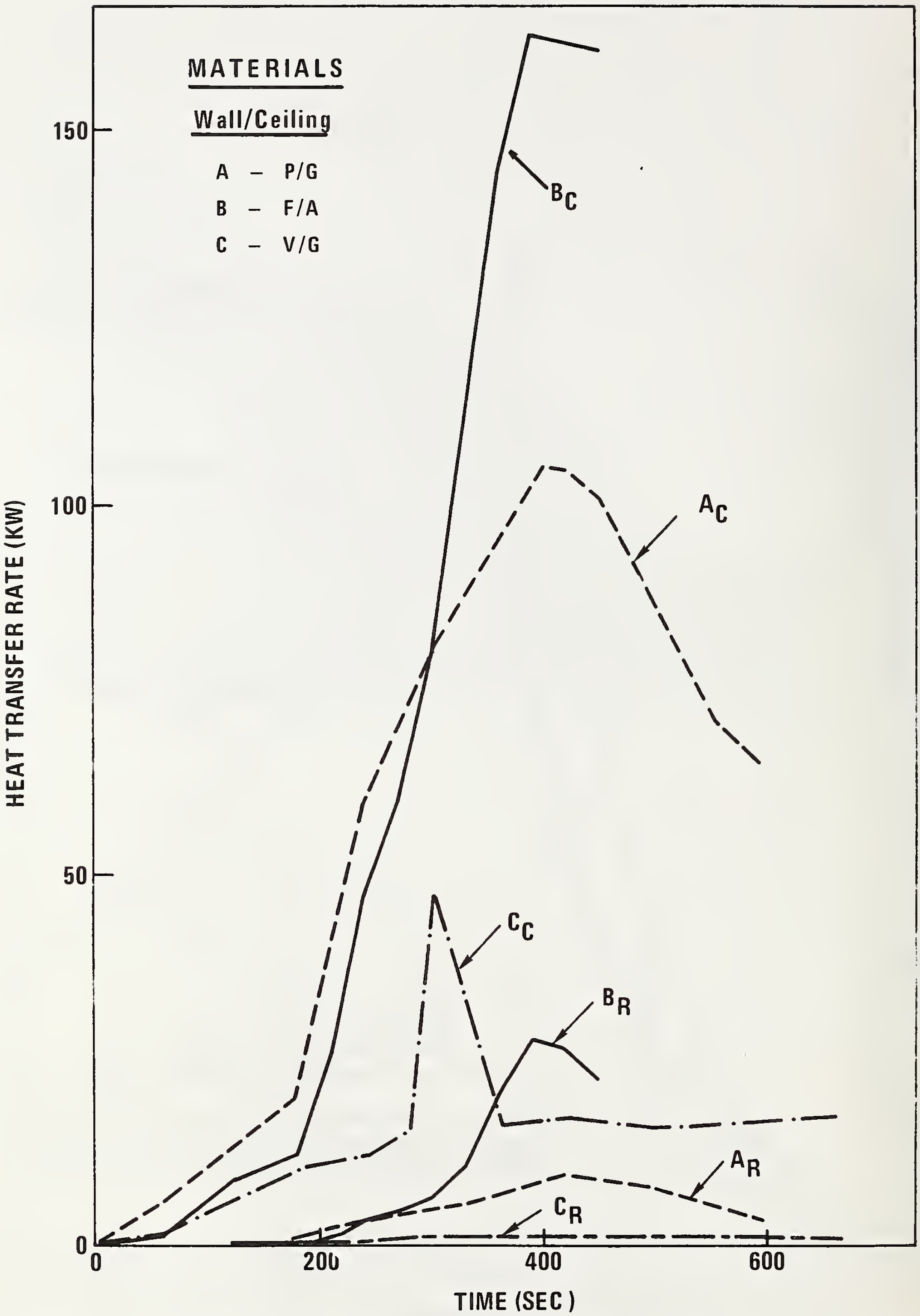


Figure 6. Convective and radiative heat - transfer - rate through the doorway to an adjacent compartment for different combinations of wall and ceiling linings. The subscripts C and R indicate convective and radiative component, respectively.

In figure 7, the maximum rates of convective and radiative energy pouring out from the fire room were plotted against the peak upper room gas temperatures for all tests performed. As indicated in the figure, the magnitude of sensible heat due to outward convective flow is more or less directly proportional to the upper room gas temperature level. This convective energy carried by the vent gas constituted a large portion of total energy leaving. Thus, the interior finish materials may be ranked for increasing fire hazard according to increasing maximum upper room gas temperature and a physically meaningful method for evaluating the hazard potential of lining materials can be attained.

As mentioned previously, one aspect of fire behavior which has a direct bearing on life safety is the level of temperature and heat flux developed from the burning of building materials and structures. As the material type and arrangement of interior finish materials had pronounced effects on the upper room gas temperature, the experimental temperature data presented in table 3 were used to examine the interrelation of these three variables. A relation has been derived using linear regression analysis to express the individual temperature rise contributions of the wall and ceiling materials to the combined maximum upper room gas temperature:

$$T_u = 0.94\,\theta_w + 0.38\,\theta_c + 122 \qquad (1)$$

where T_u is the combined maximum upper room gas temperature, in °C. θ_w and θ_c are the characteristic temperature rises assignable to the wall and ceiling materials respectively, in °C. The value of θ for each material is determined by measuring the maximum upper room gas temperature when the material lines the walls and painted gypsum board covers the ceiling, and then substracting 107°C which is the maximum upper room gas temperature when both the walls and ceiling are lined with asbestos-cement board. When the flames fail to reach the ceiling, θ_c should be taken to be zero. It is important to note that these characteristic temperature rises depend significantly on the room corner test parameters such as crib size, room size, ventilation conditions, and insulation properties of the remainder of the room. The empirical correlation expressed by equation 1 provides a close approximation to the data points, with a correlation coefficient of 0.99, computed by the Pearsonian formula [11]. In this and succeeding cases, a linear correlation over a limited temperature range has been assumed in order to simplify the initial approach.

In considering the hazard of heat from building fires, the time to reach full involvement of the room's combustible contents or room flashover is important. This may determine the time available for safe evacuation of building occupants and, further, rescue and firefighting operations begun prior to flashover are far more effective than those begun later. Room flashover has been simulated in our tests, by spontaneous ignition of the indicator specimens. The elapsed times for spontaneous ignition of newsprint and plywood indicators placed at the center of the floor have been correlated as a linear function of the characteristic temperature rises of the wall and ceiling materials. The results are:

$$t_{i,n} = 11.3 - 0.011\,\theta_w - 0.00002\,\theta_c \qquad (2)$$

$$t_{i,p} = 12.0 - 0.0094\,\theta_w - 0.0019\,\theta_c \qquad (3)$$

where $t_{i,n}$ and $t_{i,p}$ are the ignition times in minutes of newsprint and plywood indicators respectively placed at the center of the floor. These two empirical equations are least square data fits applicable for $t_i \leq 9$ minutes, and have correlation coefficients of 0.85 and 0.76, respectively.

Figure 8 illustrates the variation with time of the smoke density measured at three locations. Similarly, figure 9 shows the concentrations of carbon monoxide, carbon dioxide and oxygen within the fire room. The upper room gas

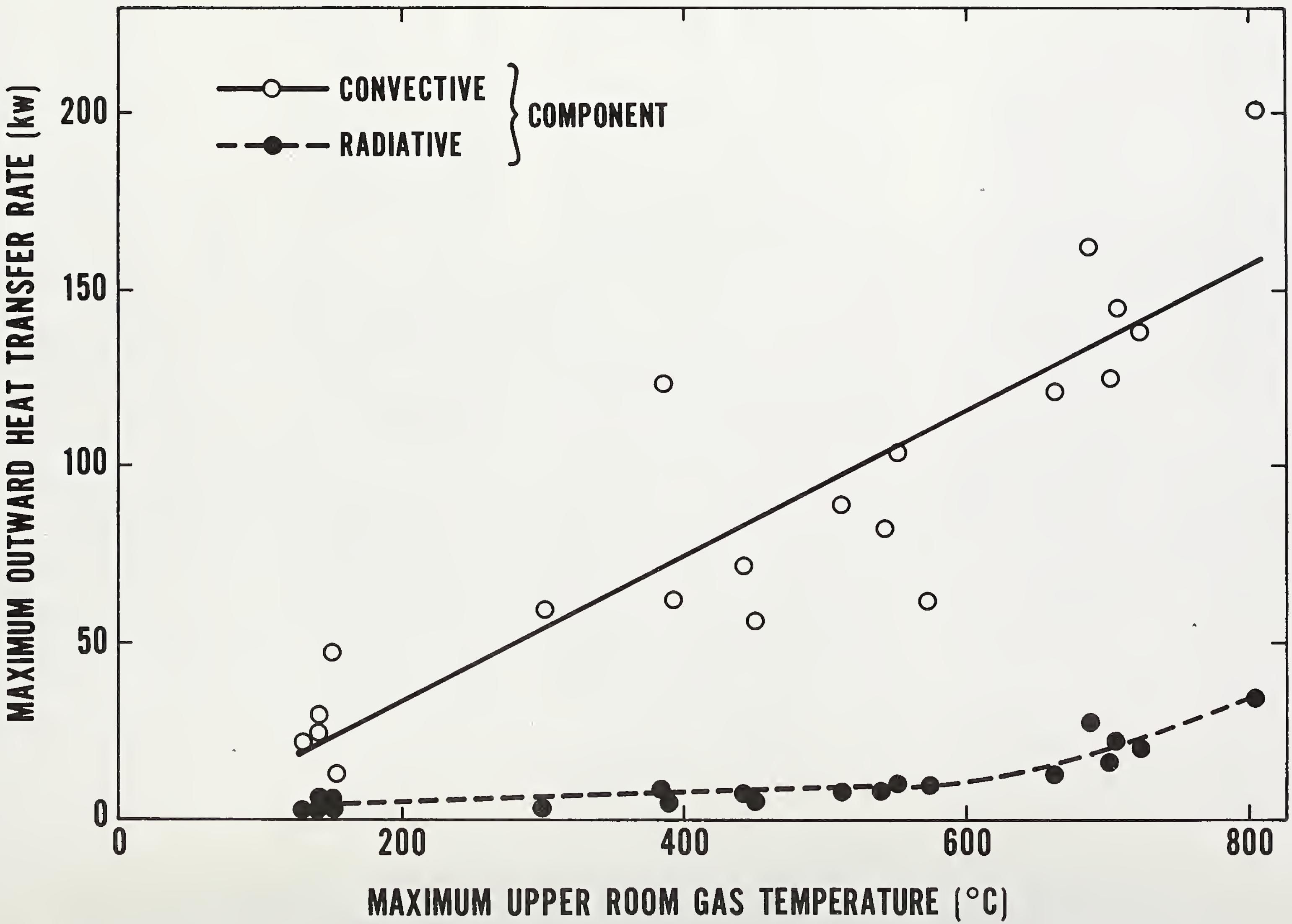


Figure 7. Relationship between the maximum upper room gas temperature and the maximum rates of convective and radiant energy transferred to the outside through the doorway.

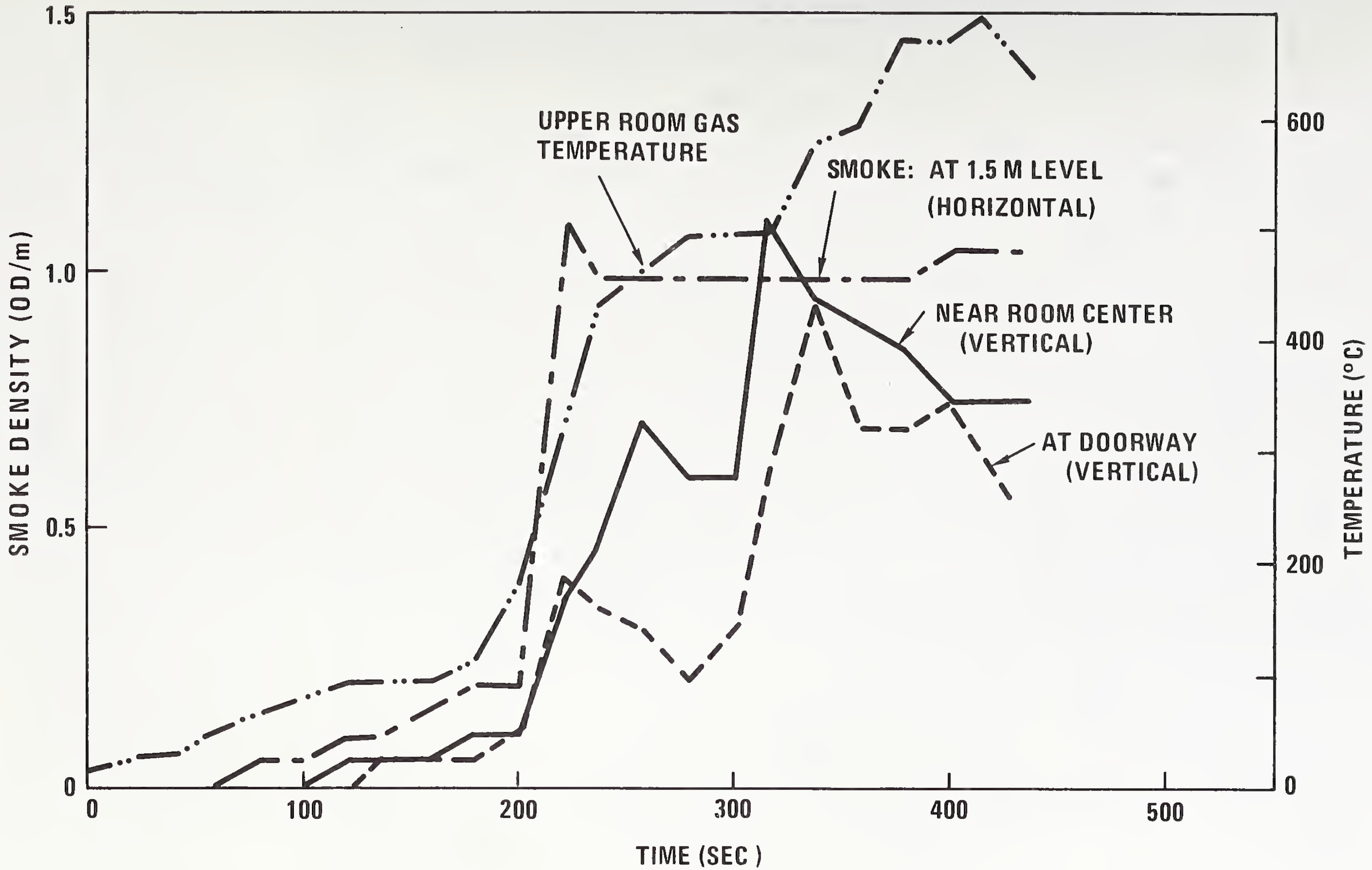


Figure 8. Smoke density measured at various locations and the upper room gas temperature for fir plywood walls and acoustic tile ceiling.

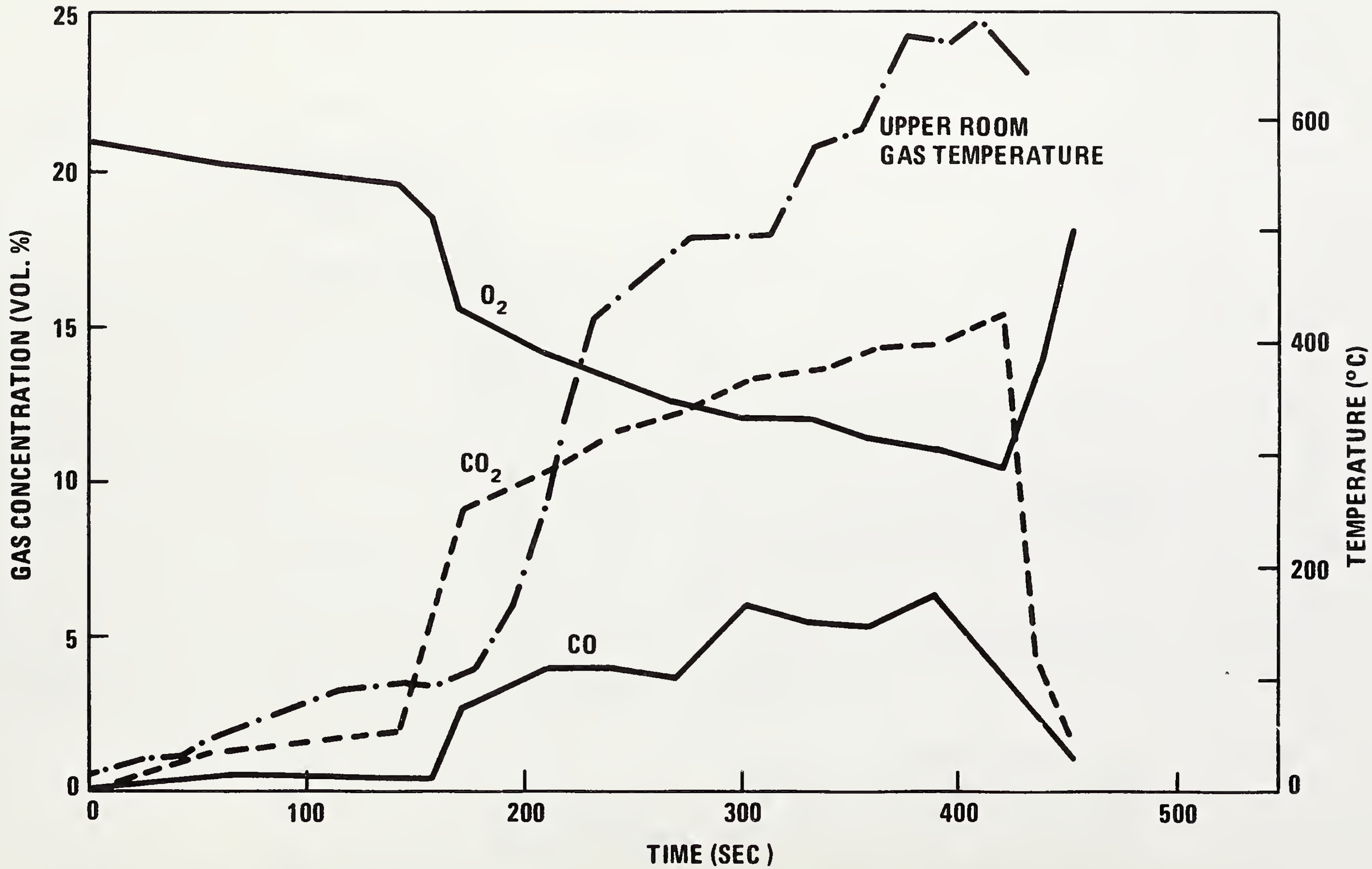


Figure 9. Concentrations of combustion gases within the fire room for fir plywood walls and acoustic tile ceiling.

temperature has also been plotted for comparison. Due to the circulation pattern with cool air entering the fire room at low level and hot flue gases vented out at the upper part of the doorway, the smoke density was stratified with a maximum level near the ceiling and minimum near the floor especially in the early part of a test. This is indicated in figure 8, where the smoke density measured horizontally at the 1.5 m level was greater than that determined vertically. This difference is reduced after approximately 5 minutes. The figure also suggests that smoke density closely paralleled the average temperature of the gases within the upper half of the fire compartment. The concentrations of carbon monoxide and carbon dioxide increased, and the oxygen level decreased as the fire developed since the consumption rates of oxygen for chemical reaction exceeded the inflow of oxygen into the compartment, (see figure 9). It was found that at the peak of the fire, the oxygen concentration and smoke density decreased sharply, and carbon monoxide and carbon dioxide showed marked increases.

The smoke concentration near the fire and throughout a building is a major concern for safe evacuation during a fire. Although the weight concentration of smoke was not measured, the total amount of smoke produced can be expressed in terms of a smoke quantity, which is defined here as the smoke density multiplied by the volume in which the smoke particles disperse. The total smoke quantity is equal to the sum of the quantity of smoke remaining within the enclosure and that leaving the fire compartment. The measured outflow smoke quantity adopted is the time integrated value of the product of the smoke density and volumetric flow rate of the effluent gas at the open doorway. The outflow smoke represents the major smoke component for this experimental arrangement. The total rate of smoke production during full-scale tests with painted gypsum board ceiling and various types of finish materials as wall linings are plotted as a function of time in figure 10. As shown in the plots, particle board and melamine finished hardboard generally had higher rates of smoke production, and vinyl-covered gypsum board, which only burned partially, the least. The early increase in smoke production during tests with particle board and Lauan plywood may be attributed to their shorter times required for ignition. Also, the reduction in total amount of smoke produced in the latter stage of the test reflects the lower smoke density when the room temperature approaches a maximum.

Figure 11 presents cumulative smoke components within and outside the fire compartment for the tests involving various combinations of wall and ceiling lining materials. Inspection of figure 11 shows that the burn room smoke quantity levels peaked out between 4 and 7 minutes and dropped off gradually due to decreasing smoke density as a result of smoke particulate coagulation or decomposition with continuous increase in the room temperature. The amount of smoke within the fire room comprised approximately 5 percent of the total smoke produced during the 8 minute period. Figure 12 shows cumulative smoke produced as a function of time for tests with different wall linings.

5. COMPARISON WITH LABORATORY TEST METHODS

There are a variety of small-scale and medium-scale laboratory devices presently available for measuring ignitability, surface flammability, heat release rate and smoke developed characteristics of materials. In order to determine if a useful correlation could be established between laboratory and full-scale test procedures, the results obtained by these room corner tests on eight different types of interior finish materials were compared with those obtained by several new and established test methods. A possible application of this information would be to help quantify the hazard characteristics of a total system involving the interaction of materials.

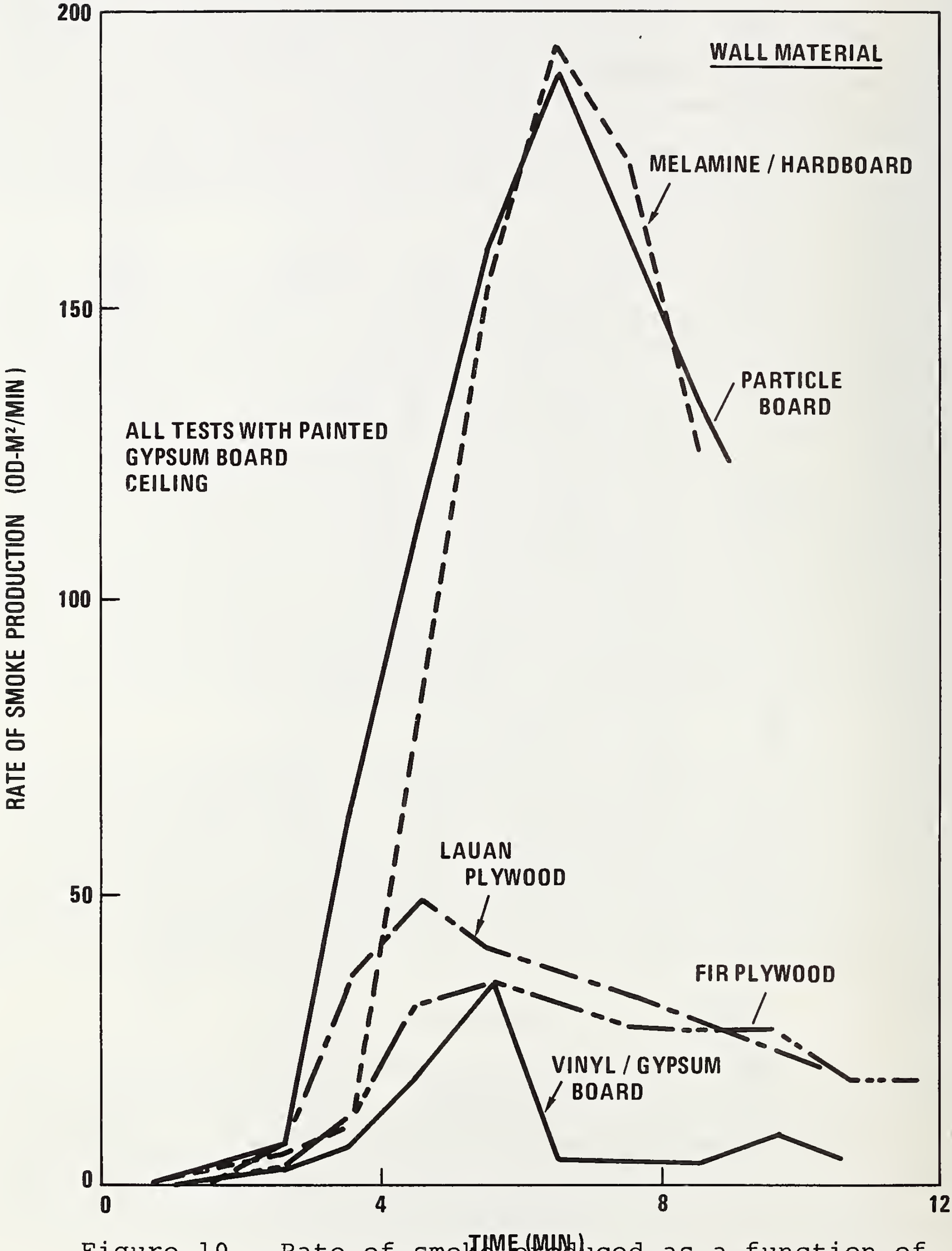


Figure 10. Rate of smoke produced as a function of time during room corner tests with different types of wall materials.

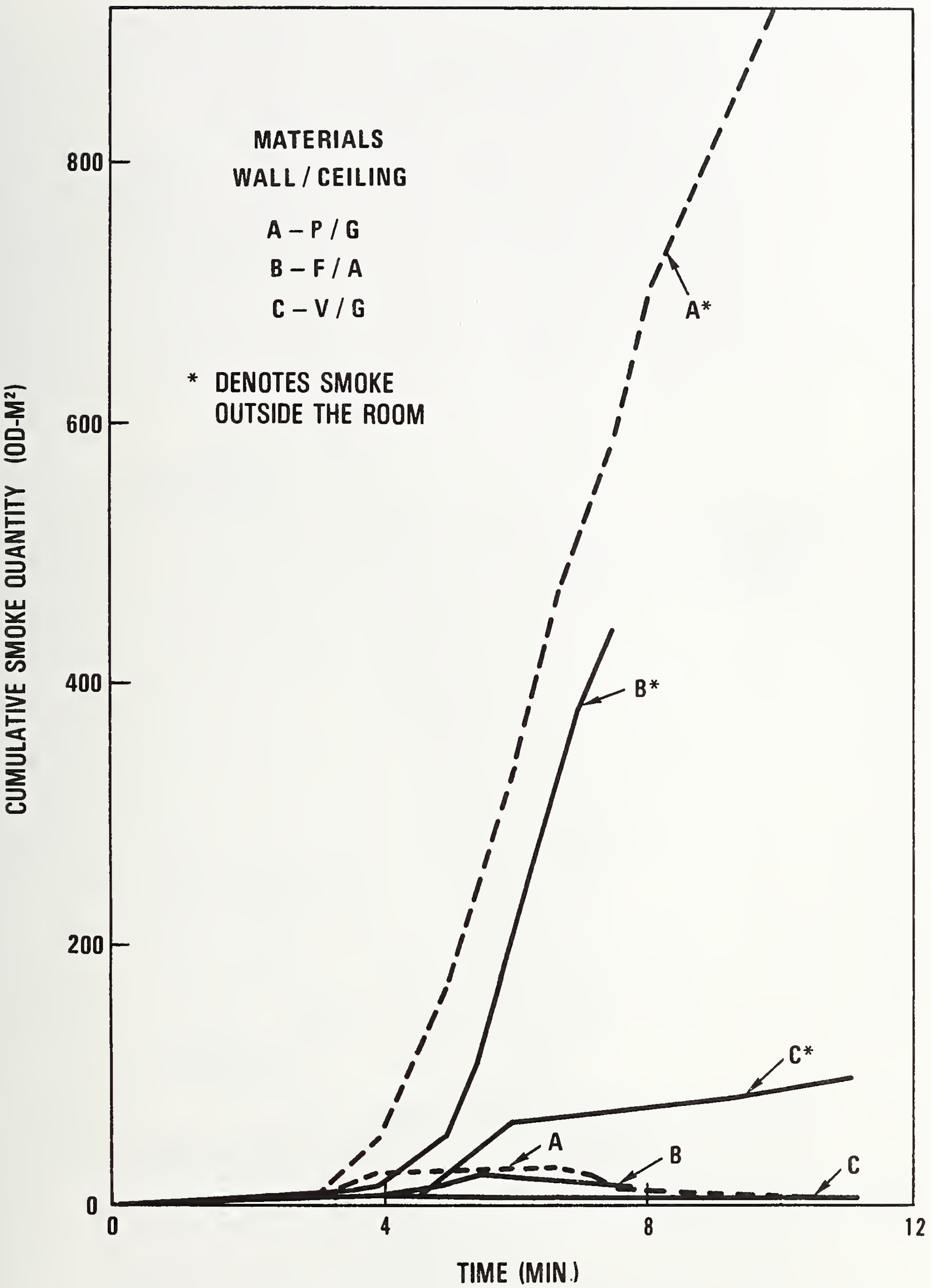


Figure 11. Cumulative smoke components within and outside the fire room for different combinations of wall and ceiling linings.

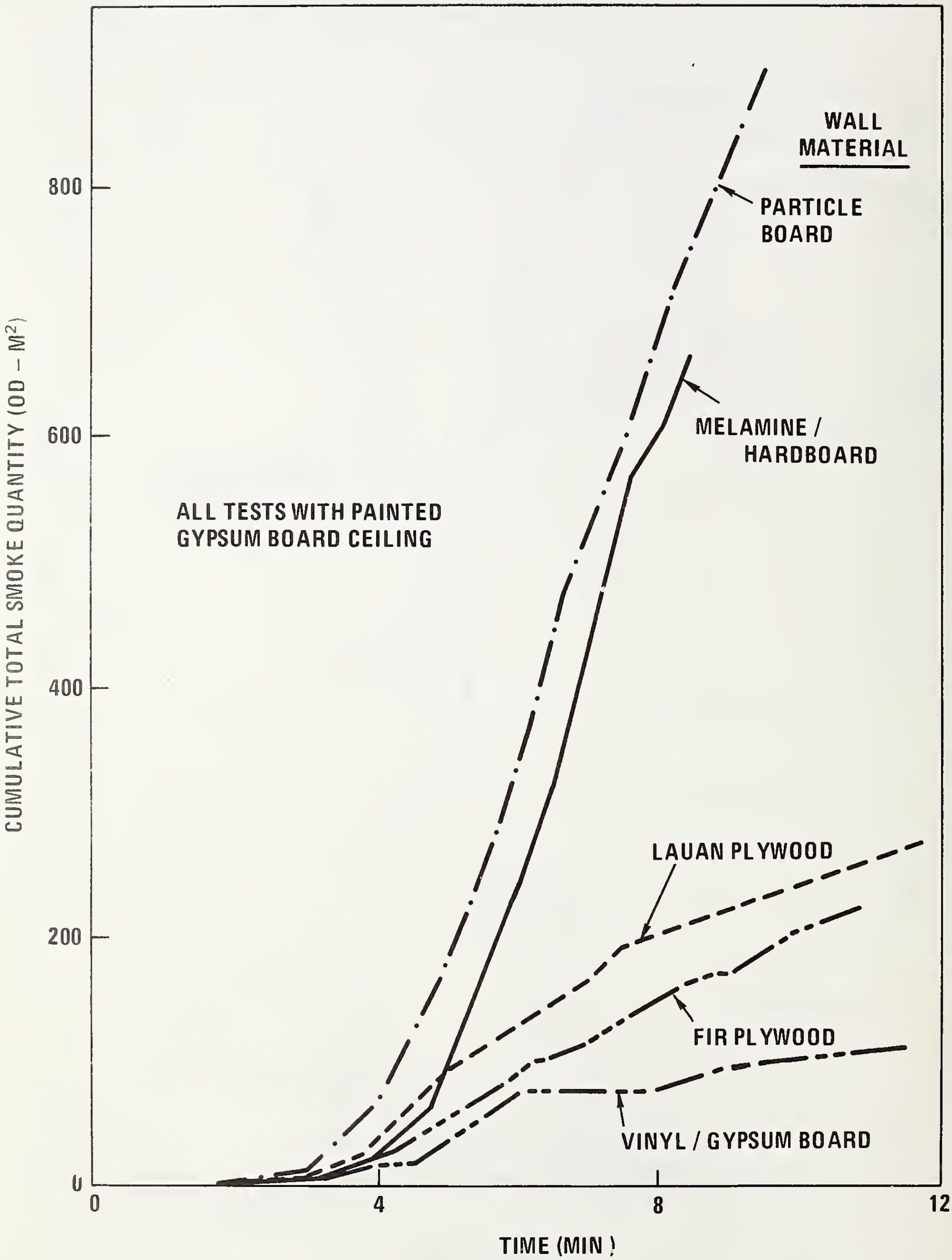


Figure 12. Cumulative smoke produced as a function of time during room corner test for fires involving different types of wall linings.

5.1. Ease of Ignition

A laboratory test apparatus for ease of ignition by flame impingement, recently developed at NBS [12], was used to determine the ignition time sustained burning for each of these finish materials. The results of small-scale tests on ease of ignition along with surface flammability, heat release rate and smoke generation properties for each selected interior finish material are listed in table 1. A comparison plot of the laboratory test results versus the ignition times obtained from full-scale room corner tests is presented in figure 13. Excluding coated acoustic tile, and painted and vinyl covered gypsum boards, which did not sustain ignition during the laboratory tests, the correlation of ignition times between the laboratory method and the room corner test for the lining materials examined was generally fair. In the laboratory test, the assumed criterion of sustained ignition was if the specimen continued to flame for at least 1 minute after removal of the exposure flame. Table 5 summarizes the expressions for the regression line obtained from the least squares method, residual standard deviation, and correlation coefficient to describe the degree of linear relationship between the regression line and the measured values of the variable involved.

5.2. Flame Spread

Both ASTM E84 and E162 standard test methods [13,14] are conventionally used for rating and classifying materials according to their surface flammability. Although there is little corroboration on the relationship between fire ratings or indices obtained from these tests and the actual level of fire hazard, and although present technology is unable to assess the impact of the environmental conditions which may also be important, it is commonly believed that these standard tests can provide data indicating relative fire spread hazard of the materials based on "simulated fire" conditions. For this research program, the information which will assist in translating the hazard ratings of these laboratory tests to performance criteria for safe use of the lining materials is of prime interest and desirable. It has been stated here that maximum upper room gas temperature is an important indicator of fire hazard--hazard to flashover in the room of fire origin and hazard of fire extension or exposure beyond the room of origin. It would be useful to assess if there is any correlation between the maximum upper room gas temperature and the numerical surface flammability ratings of the two widely used standard test procedures, E84 and E162. Since it is usually contended that the absolute numerical rating obtained from these tests is less significant than the relative ranking of the materials, it may be sufficient to find that the upper room gas temperature is a monotonic function of the respective ratings. A particular monotonic functional relation, namely, a linear relationship between these variables has been chosen to study possible correlations at the present time. The possible correlations with other types of functions have not been explored, and attention has been focused on the special correlation with hazard quantified by the upper room gas temperature.

Accordingly, the surface burning characteristics of these finish materials were measured using the tunnel furnace and the radiant panel in accordance with the ASTM E84 and E162 standard test procedures. The flame spread ratings for the wall lining materials obtained as the results of these laboratory tests are plotted in figures 14 and 15 against the maximum average upper room gas temperatures from room corner tests. For these 8 tests, painted gypsum board was the common ceiling material. As shown in the figure, the results of both laboratory tests are generally in fair agreement with those from the full-scale test, although there are several reversals in ranking. The regression line equations from correlation of these experimental data are:

$$T_u = 2.5\ F_w + 122 \quad (4)$$

$$T_u = 2.9\ I_w + 178 \quad (5)$$

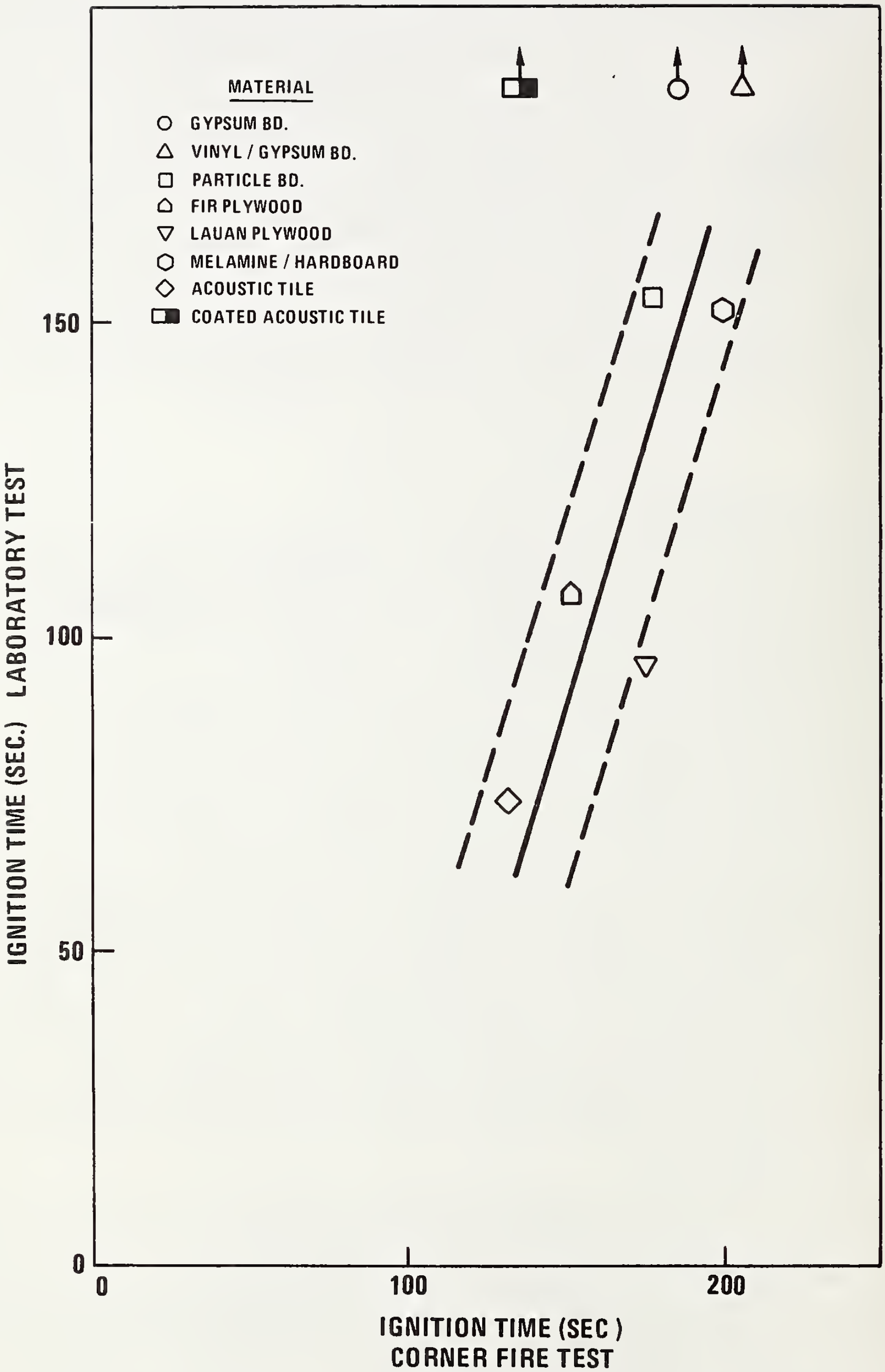


Figure 13. Comparison of ease of ignition measurements by laboratory and corner fire tests. An arrow on the top of the symbol denotes no sustained ignition for laboratory test. Dashed lines represent limits of one residual standard deviation.

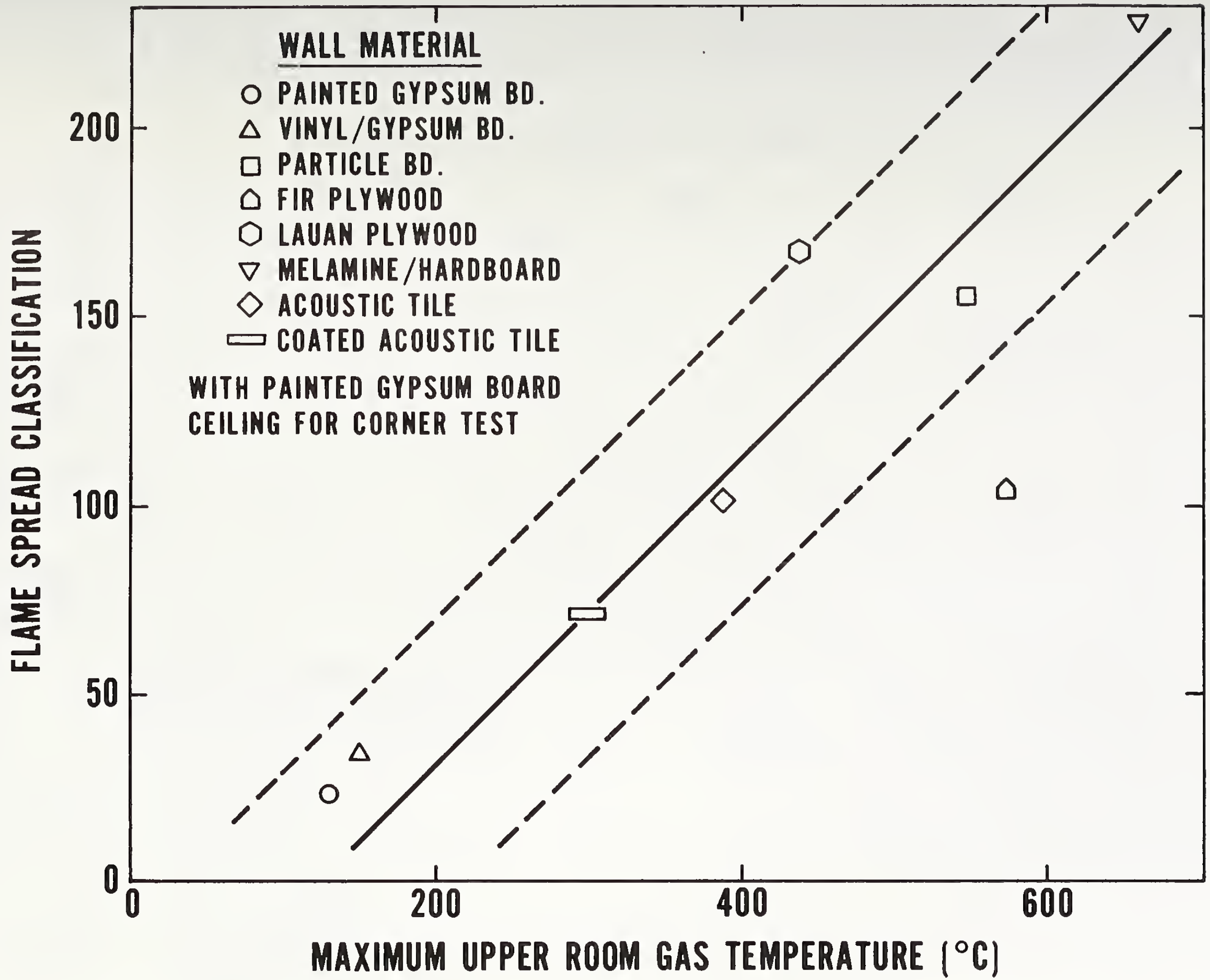


Figure 14. Comparison of flame spread classification measured by ASTM E84 Tunnel Test and the maximum upper room gas temperature by room corner test. Dashed lines represent limits of one residual standard deviation.

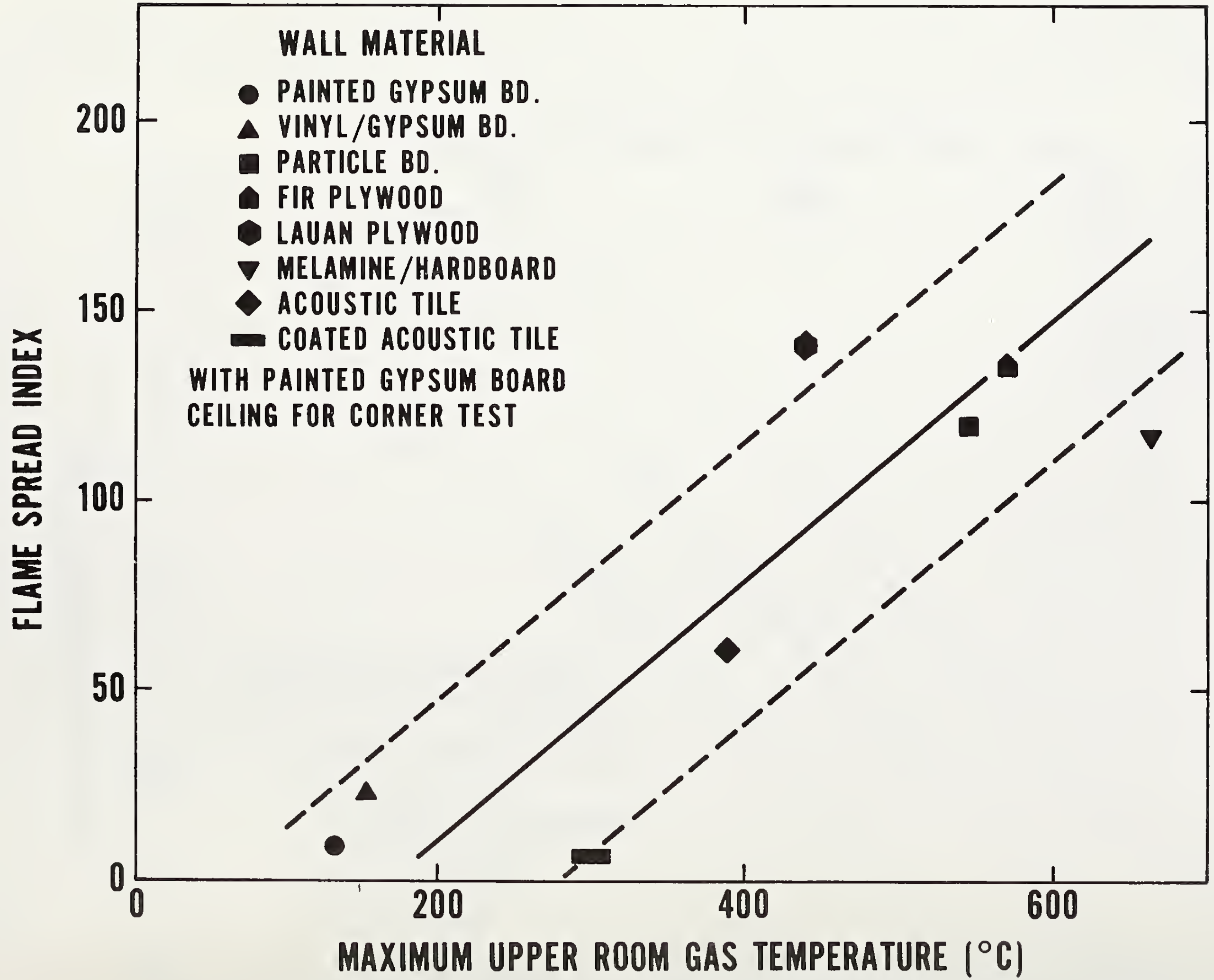


Figure 15. Comparison of flame spread index measured by ASTM E162 Radiant Panel Test and the maximum upper room gas temperature by room corner test. Dashed lines represent limits of one residual standard deviation.

Table 5. Equations of the Regression Line from Correlations of the Results of Laboratory-Scale and Full-Scale Tests

Parameter	Laboratory Method		Regression Line Equation[a]	Residual Standard Deviation	Correlation Coefficient	Reference Figure No.
Ignitability	NBS Ease of Ignition [12]		$y = 0.61\chi + 97$	17[b]	0.83	13
Flame Spread	ASTM E84 Tunnel		$y = 2.5\chi + 122$	96	0.89	14
	ASTM E162 Radiant Panel		$y = 2.9\chi + 178$	108	0.86	15
Heat Release Rate	NBS Calorimeter [15]		$y = 27.3\chi + 31$	89	0.89	16
Smoke	NBS Smoke Density Chamber	Flaming	$y = 1.83\chi$	190	0.68	17
		Non-flaming	$y = 0.927\chi$	156	0.80	17

[a] The results of laboratory-scale tests were correlated against those by the room corner test. χ denotes the figures of merit by laboratory tests, and y represents the appropriate measure results by the room corner test.

[b] Samples which did not ignite in laboratory method are not included in obtaining correlation.

where T_u = the maximum upper room gas temperature, in °C.

F_w = the E84 flame spread classification for the wall material.

I_w = the E162 flame spread index for the wall material.

As the temperature increases, a linear relation would no longer be expected due in part to increased radiation heat losses from the fire room, and in part to the non-linear effect of flame spread rate in the laboratory test.

Although there is considerable variability in the results based on these tests, it may still be possible to use E84 or E162 ratings as a crude measure of contribution to fire growth in a room. For the limited types of wall linings tested and the particular set of test conditions (room size and geometry, ventilation, wood crib ignition, etc), the critical E84 and E162 flame spread classifications corresponding to an upper room gas temperature of 540 $\pm$ 40°C appears to be significantly below 200.

The combined contributions of wall and ceiling linings to the upper room gas temperature may be formulated in terms of an equation of the form:

$$T_u = AF_w + BF_c + C$$

However, the derivation and justification for such a relation appears to require more data than the limited number of experimental results reported here.

5.3. Heat Release Rate

The heat release rate calorimeter being developed at NBS [15] was used to determine the heat release characteristics of these selected lining materials under radiant exposure conditions simulating a fairly severe fire environment. In this test, a 11.4 by 15 cm (4.5 by 6 in) specimen was mounted vertically at the center of the calorimeter, and exposed its front face to a radiant flux of 6 W/cm^2 produced by gas-fired radiant panels. The heat release rate of the specimen was measured from the decreased rate of flow of fuel to an auxiliary burner so that the rise in temperature due to the burning of the specimen was compensated. The heat release rates and the total heat released, which was determined by integrating the heat release rate over the burning period, were based on the average of three determinations. The results are given in table 1. Figure 16 shows the comparison between the highest 1-minute average heat release rates obtained from this laboratory test measurements and the peak upper room gas temperatures derived from the room corner tests. Except for melamine-finished tempered hardboard, which liberated heat rapidly for approximately a 1-minute period during rapid burning of the entire melamine layer and then had a considerably lower heat release rate throughout the remainder of the laboratory test, the correlation between these two test parameters is reasonably good as indicated in the figure. This would be expected in a room fire, where a large portion of the initial heat released is used to raise the temperature of the room gases and enclosure walls and ceiling. The test conditions in the calorimeter are somewhat similar to the fire environment developed in the full-scale test. The regression line equation based on figure 16 is:

$$T_u = 27.3\ H_w + 31 \qquad (6)$$

where H_w = heat release rate of the wall covering material, in W/cm^2.

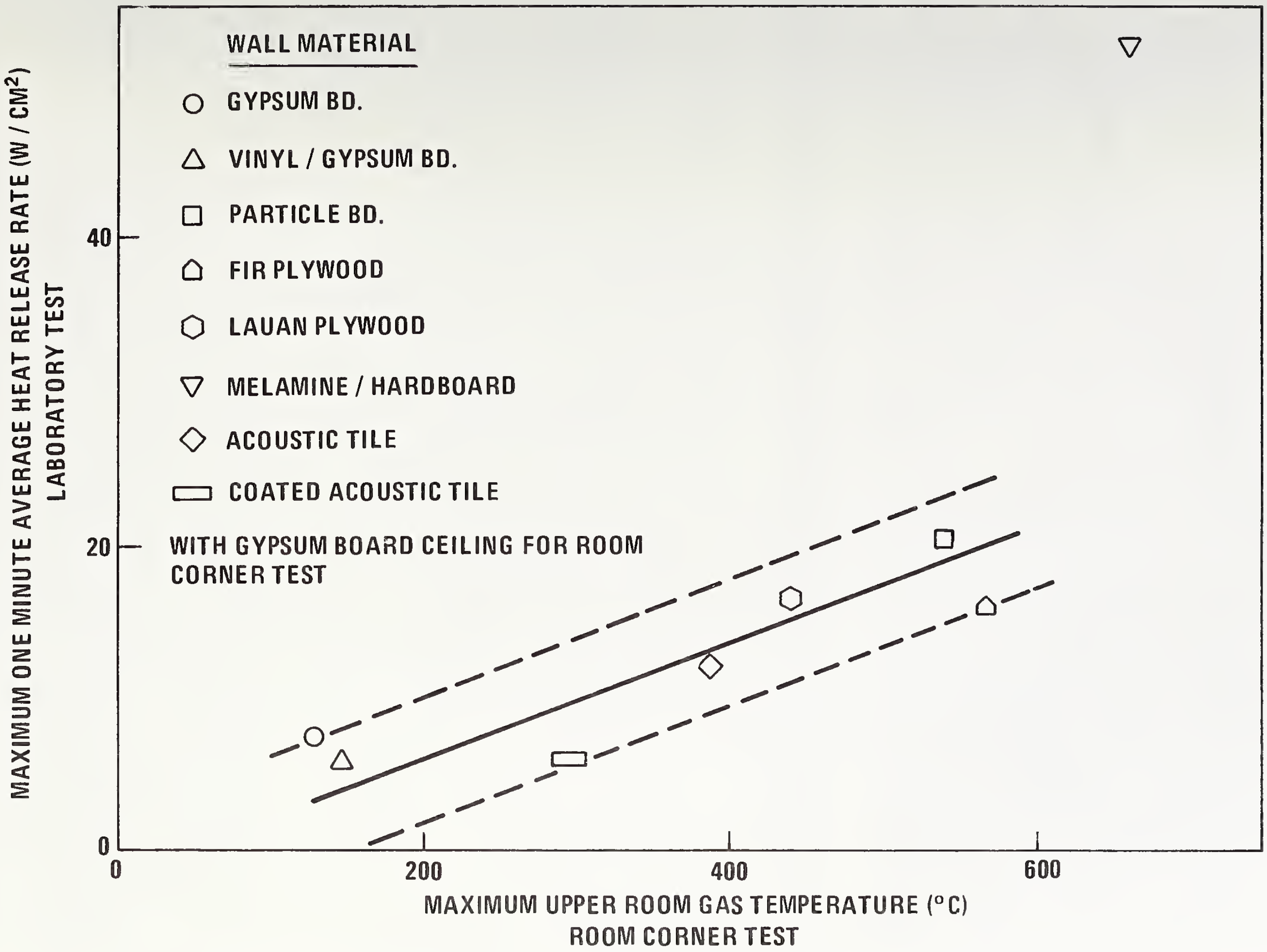


Figure 16. Comparison of the results from laboratory scale and room corner tests on heat release rate. Dashed lines represent limits of one residual standard deviation.

5.4. Smoke Generation

Consider the smoke hazard to a person trapped in a dwelling where smoke is being produced, and vented out from an adjacent room, and spreading along the ceiling. In this situation it may be difficult for the dwelling occupant to escape due to impairment of vision and/or eye irritation, and an understanding of the tolerable human smoke levels is essential. The criterion of a visible range of 13.7 m (45 ft) with a transmission of 20 percent between light source and photocell, or an optical density/m of 0.051, was suggested in the Los Angeles school burning experiments [16,117]. Wakamatsu [18], in performing a computer study of smoke movement in buildings, chose a lower limiting smoke level of 0.043 OD/m based on potential panic and unbearable eye irritation from exposure in a smoke-filled enclosure. Gross et al [19] defined a critical smoke density, which mainly relates the visibility of objects to smoke obscuration and corresponds to a level of 0.26 OD/m, based on 16 percent light transmittance over a 3.05 m (10 ft) viewing distance in a room measuring 3.8 x 6 x 2.4 m (12.5 x 20 x 8 ft) high. Bono and Breed [20] conducted an experimental study of the effect of smoke development from burning materials in a tunnel furnace on visibility in a 9.6 x 3.7 x 3.1 m (31.3 x 12 x 10 ft) high room in which the smoke was collected. From their photographic records, the visibility of the lighted exit signs in the smoke accumulation room was vague at an optical density/m of 0.27.

In order to relate and interpret the results of smoke measurements from room corner tests with those from standard test methods, a mathematical simulation of smoke movements in an enclosure with and without an opening has been developed and is presented in Appendix B.

Smoke density and time to reach a critical smoke level or obscuration time are considered important parameters for safe evacuation. Using Gross' assumption of 3 m (10 ft) with a light transmission of 16 percent as a hazard criterion, the limiting value of total smoke quantity for a small dwelling with a floor area of 7.6 m (25 ft) by 12.2 m (40 ft) and a 2.4 m (8 ft) high ceiling would be 29 OD/m^2. The time to reach this smoke level for the selected material combinations have been included in table 6 along with the cumulative quantity of smoke produced in an 8 minute period. It can be seen that the time taken to reach this smoke level ranged from 3 to 5 minutes, depending on the material type involved. Combining the regression line equation on smoke data as listed in table 5 where the total smoke quantity is evaluated at 8 minutes and equation B-10 in which a critical smoke density of 0.26 OD/m is used to substitute for $\bar{D}/L$, the critical levels of smoke ratings from the NBS smoke density chamber test method can be expressed in terms of the dwelling volume, Q^*, as follows:

$$\text{flaming exposure condition:} \quad D_{m,f} = 0.071\, Q^* \qquad (7)$$

$$\text{non-flaming exposure condition:} \quad D_{m,n} = 0.14\, Q^*$$

where D_m is the maximum specific optical density and the subscripts f and n refer to flaming and non-flaming exposures in the smoke chamber.

This visual threshold based on the potential light obscuration hazard of smoke in the buildings represents an approach which may serve as a criterion for selecting appropriate finish materials as interior linings. It should be noted that the empirical coefficient relating the room volume to the smoke ratings depends upon the time interval during which the smoke quantities of selected finish materials were evaluated.

Laboratory tests were conducted to evaluate the smoke producing properties of the interior finish materials using the smoke density chamber [21]. The maximum specific optical density, D_m obtained from the smoke density chamber test procedure (separate flaming and non-flaming modes), was plotted against the total smoke quantity, derived from the room corner test measurements as

Table 6. Data on Cumulative Quantity of Total Smoke Produced in Full-Scale Tests

Materials		Cumulative Total Smoke Quantity		Time to Cumulative Smoke Quantity = 29 OD-m^2 (min)
Walls	Ceiling	Time (min)	Smoke Quantity (OD-m^2)	
Lauan Plywood	Painted Gypsum Board	8	203	3.53
Painted Gypsum Board	Painted Gypsum Board	8	57	4.23
Vinyl/Gypsum Board	Painted Gypsum Board	8	81	4.93
Particle Board	Painted Gypsum Board	8	702	3.11
Melamine/ Hardboard	Painted Gypsum Board	8	617	4.20
Coated Acoustic Tile	Painted Gypsum Board	8	96	4.0
Fir Plywood	Painted Gypsum Board	8	147	4.3
Acoustic Tile	Painted Gypsum Board	8	66	5.45
Fir Plywood	Acoustic Tile	7.3	457	4.1

shown in figure 17. For these materials, the rate of smoke generation was higher under the non-flaming than under the flaming exposure in the smoke density chamber. Equation B-12 derived in Appendix B suggests that a linear relationship exists between total smoke quantity and the maximum specific optical density if both open and closed enclosures have similar smoke source characteristics, i.e., smoke generation rate. The poor correlation between the value of maximum, specific optical density in the smoke density chamber method and full-scale test results may be attributed to several factors, including differences in the levels of heat flux acting on the test material and the temperature buildup within the fire compartment. These two variables affect the rates of smoke production and particulate vaporization, coagulation or deposition. It should be noted that the time intervals at which the optical density reached maximum varied with the test materials in the smoke chamber test. With the use of equation B-12 along with the regression line equations listed in table 5, and an exposed surface area of 0.00422 m^2 for A_c, the ratios of the total amount of smoke produced in the ventilated fire room to that generated in the closed smoke chamber were found to be 440 for flaming exposure and 220 for non-flaming exposure conditions, respectively.

6. SUMMARY AND CONCLUSIONS

The following conclusions are based on a limited series of full-scale fire growth tests in a room and corresponding small-scale laboratory tests on a series of wood and gypsum board-base wall and ceiling lining materials. The objectives were (1) to evaluate the extent of fire growth attributable to the interior finish materials when exposed to a typical low intensity fire source, and (2) to assess possible correlations between fire behavior during the fire buildup process and numerical values from standardized laboratory tests. Additional data, involving tests on a greater variety of wall and ceiling materials are needed.

While the conclusions reached are not applicable beyond the actual types of materials and experimental conditions employed, it was the intent of this work to outline techniques which might be useful in assessing to what extent real fire hazards may be predicted by laboratory tests. The conclusions are necessarily limited to the particular test conditions selected for initial study and the specific arrangements and values of the important variables which include: room size and shape, single open doorway serving as source of ventilation, exposure of wall and ceiling panels to a corner fire source, and a wood crib simulating the fire intensity and flame height (not extending to the ceiling) of a small chair or a large wastebasket.

1. A small fire which starts in a chair or wastebasket may result in a room fire which is out of control in 6 to 9 minutes, or which is limited in intensity and extent for 20 minutes, depending upon the fire properties of the wall and ceiling lining materials.

2. Both temperature and heat flux measurements indicate that the downward radiation emitted by the hot gases and the heated ceiling and walls in the upper half of the fire room play the dominant role in causing ignition of the combustibles situated below.

3. A useful measure of the development of a compartment fire is the average temperature of the gases within the upper half of the fire room. This temperature provides a correlation with the ignition of typical combustible contents such as newsprint and plywood, and represents an index of fire hazard in terms of potential involvement of all room combustibles (flashover) plus extension beyond the room of fire origin. A temperature in the range of 450 to 650°C appears to be the dividing region between limited and full involvement. Under this test configuration, the upper room gas temperatures corresponding to spontaneous ignition of newsprint and plywood placed

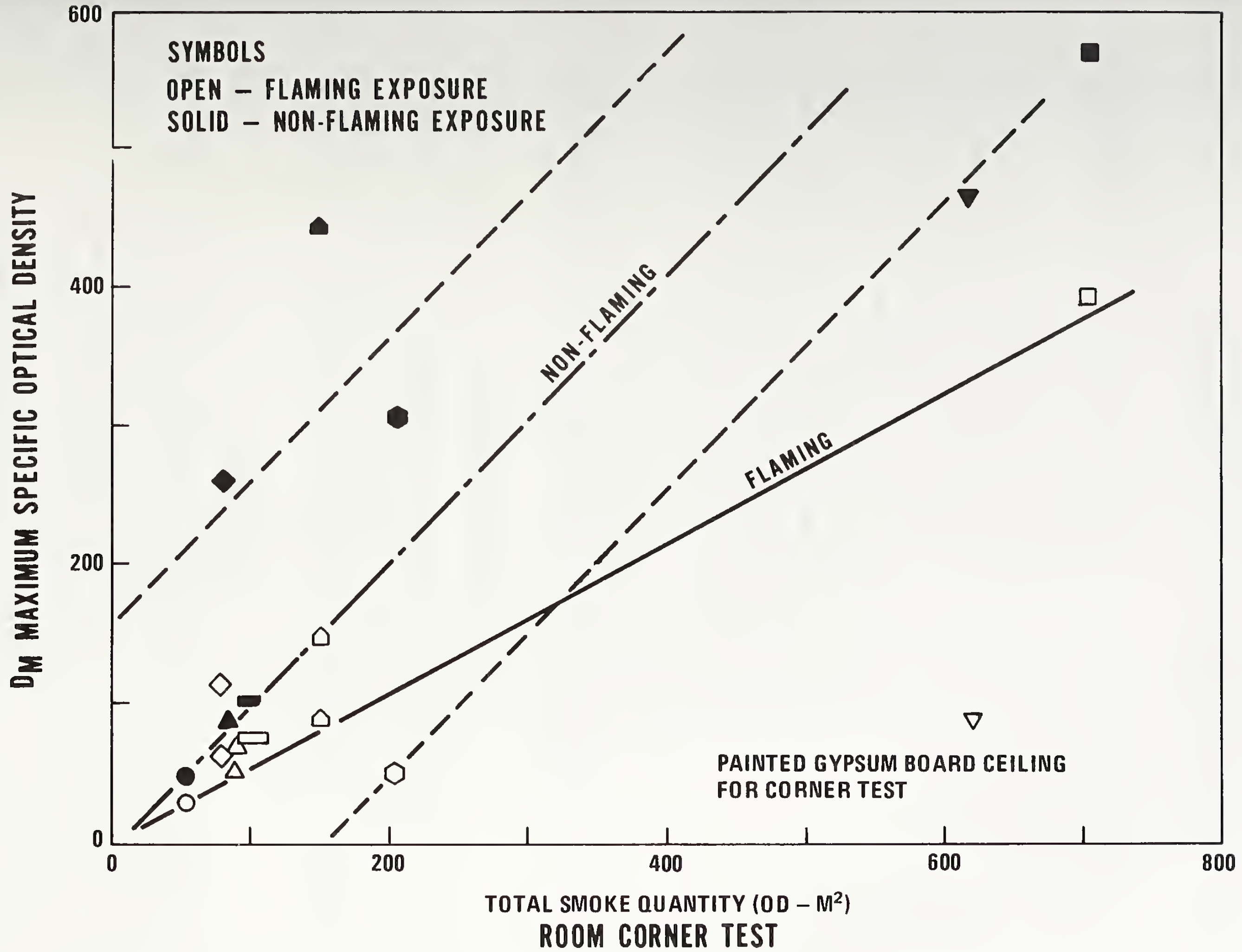


Figure 17. Comparison of the results of smoke measurements by Smoke Density Chamber and Corner Fire Tests.
□ - Particle Board, ▽ - Melamine/Hardboard, ⬡ - Lauan Plywood, ⌂ - Fir Plywood, ▭ - Coated Acoustic Tile, ◇ - Acoustic Tile, △ - Vinyl/Gypsum Board, ○ - Painted Gypsum Board
Dashed lines represent limits of one residual standard deviation for non-flaming exposure.

at the center of the floor were found to be approximately 540 ± 40 and 590 ± 40°C, respectively, and the times at which recorded ignitions occurred ranged from 6 to 9 minutes.

4. The wall plays a slightly more important role than the ceiling in fire growth in this test arrangement. A correlation analysis on the maximum upper room gas temperature data from the tests with selected combinations of interior linings indicates that the total contribution to the upper room gas temperature level consists of approximately 70 percent from the wall linings and 30 percent from the ceiling lining.

5. The correlations between the maximum upper room gas temperature and both the ASTM E84 flame spread classification and the E162 flame spread index, were generally fairly good, even though there were several reversals in material rankings.

6. The heat release rate based on the highest one-minute average, for an exposure of 6 W/cm^2, provides reasonable correlation with the upper room gas temperature. For comparing relative hazard characteristics of interior finish materials, particularly at different radiation exposure levels, the heat release rate calorimeter method appears to have good prospects as an evaluation tool.

7. With smoke measurement, there is no strong correlation between the results of the room corner test where wall involvement and resulting exposure is variable, and controlled uniform laboratory test conditions. It is evident that the amount of smoke produced from the burning of lining materials is highly sensitive to the levels of heat flux imposed on the materials, and the gas temperature in the upper part of the enclosure.

8. Since standard laboratory tests are not designed for evaluating fire hazards of combinations of finish materials on walls and ceiling, the room corner test can provide meaningful results and should be further developed.

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APPENDIX A. A SENSITIVITY EVALUATION OF THE ROOM CORNER TEST PROCEDURE

An estimate of the standard deviation of the replication error for a single test based on the data in table 2 can be obtained by taking the single root of the sum of the differences between the duplicate test results divided by twice the number of combinations [10]. Thus,

for the maximum upper room gas temperature $S = 27.1°C$

for the maximum smoke density $S = 0.0832$ OD/m

These correspond to coefficients of variation for replication error of 6.0% and 11%, respectively.

The combined estimate of the standard deviation of a difference between two averages of n measurements is $S\sqrt{\frac{2}{n}}$. A comparison of the differences between two averages for the capital letter conditions and the lower case letter conditions is given in table 7. The estimated standard deviations of the difference between averages of two replicate tests for each of four combinations are:

for gas temperature $S_d = (27.1)\sqrt{\frac{2}{8}} = 13.6°C$

for smoke density $S_d = (0.0832)\sqrt{\frac{2}{8}} = 0.0416$ OD/m

The multiple, t, of these standard deviations which will give a difference not likely to be exceeded by chance depends on the level of probability or confidence desired, and the number of degrees of freedom available for estimating the standard deviations. At the 95 percent confidence level, with eight degrees of freedom, the value for t is 2.31. The upper limits at the 95 percent confidence level was calculated as:

for gas temperature $\Delta = t \cdot S_d = 31.4°C$

for smoke density $\Delta = t \cdot S_d = 0.096$ OD/m

Table 7. Comparison of the Maximum Values of the Upper Room Gas Temperature and the Room Smoke Density with Change in Test Variables

Variable	Average for Capital Letters		Average for Lower-Case Letters		Difference Between Average	
	Gas Temperature (°C)	Smoke Density (OD/m)	Gas Temperature (°C)	Smoke Density (OD/m)	Gas Temperature (°C)	Smoke Density (OD/m)
Crib Size	388	0.56	523	0.88	135	0.32
Wall Material	271	0.52	640	0.92	369	0.40
Ceiling Material	409	0.68	502	0.77	93	0.09

APPENDIX B. SMOKE MEASUREMENTS IN OPEN AND CLOSED ENCLOSURES

Based on experimental observations of the light obscuration of wood smoke, Foster [22] reported that the optical density of a volume containing smoke is directly proportional to the mass concentration of smoke particles. A general theoretical analysis of the relationship between particulate properties and plume opacity has been made recently by Pilat and Ensor [23]. The generalized equation is given by

$$C = \frac{K\rho_s \ln\left(\frac{I_o}{I}\right)}{L} \tag{B-1}$$

where C is mass concentration of smoke particles, in g/m^3, K is specific particulate volume/extinction coefficient ratio, in cm^3/m^2, ρ_s is density of smoke particles, in g/cm^3, L is light path length, in m, I_o is intensity of incident light, and I is intensity of transmitted light.

The parameter K is a function of the particle size distribution, the particle refractive index, and the wavelength of light. By using the definition of optical density, D, this equation can be rewritten in the following form,

$$\frac{D}{L} = \frac{C}{2.303\ \rho_s K} \tag{B-2}$$

This equation states that for a given particle density, parameter K, and extinction path length, optical density determination is directly related to smoke mass concentration measurement.

In order to relate and interpret the results of smoke density measurements between a ventilated and a closed enclosure, an analysis of smoke movement in these systems is desirable. For derivation of the relevant equations describing these systems, the following simplifying assumptions are made:

1. The enclosure can be divided into two separate regions (upper and lower). In each region, the fluids are perfectly mixed to insure no variation in smoke concentration.

2. The velocity of air entrainment into the smoke layer is directly proportional to local velocity.

3. The rate of loss in smoke caused by coagulation, settling, vaporizing, and condensing is proportional to local smoke concentration.

Consider a ventilated enclosure where the smoke being generated from a pyrolyzing source flows beneath the ceiling and vents through the upper part of an opening, and cool air is drawn into the system via the lower portion of the same opening, and entrains upward into the smoke layer.

The equation of conservation of smoke mass for the upper region of the enclosure is given by

$$\frac{dC}{dT} + \left(\frac{V + V^1}{WSh} + k\right) C = \frac{\dot{m}''A}{WSh} + \frac{EUC^*}{h} \tag{B-3}$$

where C is mass concentration of smoke in the upper region, t is time variable, in sec V is volumetric flow rate of the exiting hot fluid, in m^3/sec, V' is volumetric flow rate of hot fluid diffusing into the lower region, k is settling coefficient, dimensionless, $\dot{m}''$ is smoke producing rate per unit surface area, in g-OD/m^2-sec, A is surface area of smoke producing source, in m^2, h is the

thickness of the upper layer, in m, E is entrainment coefficient, dimensionless, U is bulk velocity, in m/sec, C* is mass concentration of smoke in the lower region, in g/m^3, W and S are width and length of the enclosure respectively, in m.

In the lower region where the hot fluid stream circulating downward within the enclosure mixes immediately with the entering air, its smoke concentration can be obtained by macroscopic mass balance and with the assumptions of no settling out of smoke particles and negligible smoke accumulation

$$C^* = \frac{V^1 C}{V_a + V^1} \tag{B-4}$$

where V_a is volumetric flow rate of entering air.

Eliminating C* in equation B-3 with use of the above relation and integrating over a specified time interval, τ, gives

$$C = \int_0^{\tau} \frac{\dot{m}''A}{WSh} \exp\left[\phi(t-\tau)\right] dt \tag{B-5}$$

where $$\phi = \frac{(V + V^1)}{WSh} - \frac{EUV^1}{h(V_a + V^1)} + k$$

For a closed enclosure, the volumetric flow rate of hot fluid circulating into the lower region can be taken as equal to that of the cold fluid entrainment into the upper region as a reasonable approximation. With an additional assumption of no settling out of suspending smoke particles, the mass concentration of smoke in a closed system at any time interval, τ, is expressed as

$$C = \int_0^{\tau} \frac{\dot{m}''A}{WSh} dt \tag{B-6}$$

and the optical density is obtained from equation B-2,

$$D = \frac{L}{2.303K\rho_s} \int_0^{\tau} \frac{\dot{m}''A}{WSh} dt \tag{B-7}$$

For an open enclosure, the flow rate of hot fluid dispersing into the lower region can be neglected in comparison with those of the exiting and the inflow streams. The mass concentration of smoke in an open system for the case of no particulate settling out can be approximated by

$$C = \int_0^{\tau} \left[\frac{\dot{m}''A}{WSh}\right] \exp\left[\phi'(t-\tau)\right] dt \tag{B-8}$$

and the expression for optical density is

$$D = \frac{L}{2.303K\rho_s} \int_0^{\tau} \left[\frac{\dot{m}''A}{WSh}\right] \exp\left[\phi'(t-\tau)\right] dt \tag{B-9}$$

where $\phi^1 = V/WSh$.

Assuming the smoke layer to occupy the upper half of the room height, a simple expression relating the smoke density to the quantity of smoke produced and the volume of the room (or dwelling) in which the smoke is accumulating, can be obtained by differentiating equation B-9 with respect to time, or simplifying equation B-3 with use of the preceding assumptions and equation B-2, and integrating over a specified time interval, τ. This results in the relation

$$\frac{\bar{D}}{L} = \frac{2}{Q^*}\left[\int_0^\tau \frac{VD}{L}\,dt + \frac{WShD'}{L}\right] = \frac{2}{2.303K\rho_s Q^*}\int_0^\tau \dot{m}''A\,dt \tag{B-10}$$

where $\bar{D}/L$ is the average smoke density, in OD/m.

Q^* is the total volume of the room or dwelling, in m^3.

D/L and D'/L are the average smoke density measured at time t, at the doorway and inside the fire room respectively, in OD/m.

Division of equation B-10 with the relation expressed by equation B-7 and rearrangement of the resultant equation yields the relationship between the total amount of smoke produced and optical density measurements in open and closed enclosures.

$$\frac{\int_0^\tau \dot{m}_o''A_o dt}{\int_0^\tau \dot{m}_c''A_c dt} = \left(\frac{L_c}{L_o}\right)\left(\frac{W_oS_oh_o}{W_cS_ch_c}\right)\left[\frac{D_o'}{D_c'} + \frac{1}{W_oS_oh_oD_o'}\int_0^\tau V_oD_o dt\right] \tag{B-11}$$

where D is optical density, and the subscripts c and o denote the closed and open systems respectively.

By introduction of the specific optical density, D_s, defined as $D_s = Q_cD_c'/L_cA_c$, into equation B-11, an expression relating smoke measurements between full-scale room corner test and the NBS smoke density chamber method can be obtained as

$$\frac{\int_0^\tau \dot{m}_o''A_o dt}{\int_0^\tau \dot{m}_c''A_c dt} = \frac{\left[\frac{Q_oD_o'}{L_o} + \int_0^\tau \frac{V_oD_o}{L_o}dt\right]}{A_cD_s} \tag{B-12}$$

where $Q_o = W_oS_oh_o$, the room volume containing the smoke particles in the fire room, and

$Q_c = W_cS_ch_c$, the chamber volume in which the smoke particles disperse.

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16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

A variety of wall and ceiling panels in a full-scale room corner have been exposed to a fire from a standardized wood crib, simulating the environment produced by the burning of a single item of furniture, to evaluate their contribution to room fire growth. A total of twenty room corner tests were performed using selected combinations of eight wood-base and gypsum board-base interior finish materials on the walls and ceiling. Gas temperatures and velocities, surface temperatures, heat fluxes, smoke densities, and concentrations of oxygen, carbon dioxide and carbon monoxide were measured. Ignition times of newsprint, cotton fabric and plywood in the lower part of the room were also recorded. The results of these full-scale tests were compared with laboratory tests of the ease of ignition, surface flame spread, heat release rate and smoke generation on the same materials. The maximum upper room gas temperature has been found to agree with the ignition of such indicators as newsprint and plywood, and to represent a measure of fire hazard in terms of potential involvement of all combustible contents or room flashover. A temperature range of 450 to 650 °C appears to be the boundary between limited and full involvement.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Buildings; fire growth; flame spread; heat release; interior linings; material ignitability; performance criteria; room fires; smoke; wood crib.

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